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TITLE THE PETROLOGY OF CLAY-RICH BEDS IN THE TURONIAN (UPPER CRETACEOUS) OF THE ANGLO-PARIS BASIN

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October 1990

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A thesis submitted in partial fulfilment of the
requirements of the Council for National Academic Awards
for the degree of Doctor of Philosophy

October 1990

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ABSTRACT

Clay-rich beds ('marl bands') in the Turonian of the Anglo-Paris Basin are primary features reflecting a sudden, sharp increase in non-carbonate deposition on the sea-floor. They differ from omission surfaces because they are not rhythmic, and usually only occur during eustatic falls in sea-level. Subsequent to their deposition they have been modified by bioturbation and diagenesis. Marl bands containing a marl seam originated from a single, large influx of non-carbonate material. Flaser marls may have been formed from either a localised decrease in the amount of non-carbonate material deposited, or the deposition of several smaller pulses of non-carbonate material interspersed with white chalk sedimentation.

Mineralogical investigation shows that they contain the same non-carbonate constituents as adjacent white chalks although the relative proportions of the two main clay minerals (smectite and illite) differ markedly in higher Turonian marls. The variation in clay mineral composition seems to reflect fluctuations in sea-level.

Dinoflagellate cysts and the calcareous nannofauna do not appear to have been affected by marl band formation. In contrast, benthic foraminifera reflect the change in suface conditions with a marked decrease in the epifauna, and little change in the infauna.

Stratigraphically, geochemical patterns reflect changes in the overall composition of the clay fraction, making it possible to suggest in which of the two principal clay minerals each clay associated element occurs. Rare-earth element patterns show that the non-carbonate fraction of both white and marly chalk is of detrital origin. Oxygen stable isotope data implies that the formation of a marl is accompanied by a small (2-4°C) drop in ocean temperature.

Analysis of a series of samples from widely spaced localities within the Basin shows that individual marls can be geochemically fingerprinted, and confirms the established lithostratigraphic correlations. Using this method, samples of previously uncorrelated marls from within and below the Chalk Rock and Spurious Chalk Rock can be allocated 'Basin' names. An attempt to correlate Northern Province marls with those in the Anglo-Paris Basin was unsuccessful.

It is proposed that marls are formed as a result of erosion of clay-rich sediments from the borders of proximal emergent massifs at times of increased current activity induced by eustatic sea-level falls.

CONTENTS

VOLUME 1

1. INTRODUCTION

1.1 INTRODUCTION AND AIMS OF THIS PROJECT

Clay-rich beds, often termed marl bands, occur in much of the Middle and Upper Chalk of the Anglo-Paris Basin. In recent times they have formed part of the basis for very detailed lithostratigraphic correlations in the Anglo-Paris Basin, and in Lincolnshire and Yorkshire. These lithostratigraphic schemes suggest that individual marl bands extend over thousands of square kilometres. Despite their great stratigraphic value, relatively little is known about their origin and composition.

The aim of this project is to improve our knowledge of marl bands and to discover how and why they were formed. Detailed field examination has been followed up by extensive laboratory studies of particular aspects relating to their sedimentology, mineralogy, micropalaeontology, geochemistry and diagenesis. Comparison with other primary sedimentary features of chalks such as omission surfaces and and hardgrounds, and diagenetic features such as clay-rich flasers, has also been undertaken to see if there is a common link. It is hoped that through this work the origin and post-depositional history of marl bands, and the Chalk as a whole, can be more fully explained.

1.2 ORGANISATION OF THESIS

The remainder of this Chapter is intended to provide the reader with an introduction to the Upper Cretaceous concentrating on aspects, such as palaeogeography and hydrography, which may have influenced marl band formation. A brief review of previous work on marl bands, and discussions concerning sedimentological and lithostratigraphical terminology are also included.

Chapter 2 concentrates on chalk sedimentology and diagenesis, with particular reference to marl bands and omission surfaces. Diagenetic processes are examined to see what effect they may have on primary sedimentary features. Models are proposed to explain the formation of marls

and omission surfaces, and a classification scheme for marl bands is introduced.

Mineralogical data from marl bands are presented in Chapter 3. Particular emphasis has been placed on the mineralogy of the non-carbonate fraction from marls and and also adjacent white chalks, techniques used include X-ray diffraction examination of the clay and fine silt fraction, and microprobe examination of coarser grains.

Chapter 4 contains the results of petrographic examinations, which have concentrated on the comparison of marls and adjacent white chalks in thin section, and the examination of diagenetic textures within marls.

Chapter 5 examines the effect that the formation of marls had on the micro- and nannofaune.

Detailed geochemical studies are presented in Chapter 6, with examination of major, trace, rare-earth, stable isotope, and carbonate associated element trends across one marl band. Stratigraphic trends are examined using a series of samples from the Turonian of Sussex.

In Chapter 7, a direct comparison of the clay associated elements from different marls and the same marl collected from different localities using aluminium normalised values is undertaken. A successful attempt is made to geochemically fingerprint individual marls collected from different localities within the main part of the Basin, and this is then extended into the condensed succession containing the Chalk Rock. An apparently unsuccessful attempt is made to geochemically correlate the Chalk of Lincolnshire and Yorkshire with the Anglo-Paris Basin.

The summary and conclusions are presented in Chapter 8, along with a proposed model for the formation of marl bands and a comparison with the Plenus Marl Formation and marls found in the German chalk.

All plates and figures have been grouped together in Volume 2 in order to make the reading of the thesis easier.

Appendices contain: detailed descriptions of all the marls examined during the course of this project, the raw geochemical data used in Chapters 6 and 7, details of the analytical methods used, and stratigraphic logs of all localities examined.

1.3 TERMINOLOGY AND FIELD CLASSIFICATION OF CHALK

1.3.1 Introduction.

In the Nineteenth Century chalk was described in loose terms as it appeared at outcrop, for example Phillips (1821) used the terms 'hard chalk marle', 'soft chalk marle' and 'chalk containing a high proportion of organic material'. This form of classification continued into the Twentieth Century with Jukes-Browne and Hill (1903) noting that 'there are many varieties of chalk, some soft and some very hard'. In recent years the number of sediment types recognised has greatly increased in number (see Wood and Smith, 1978; Jarvis and Woodroof, 1984; and Kennedy and Garrison, 1975). Furthermore, some workers are now starting to apply a microscopic classification scheme (Jørgensen, 1986; Quine, 1988), although this has only been rigorously applied to marginal areas of the Anglo-Paris Basin, and the North Sea. In the main part of the Anglo-Paris Basin, where there are abundant exposures, the emphasis is still on field observation rather than microscopic classification. At present there is no formal classification scheme, for the remainder of this work the following scheme will be used:

1.3.2 Terminology and field classification of white chalks

White Chalk:	Composed of a mixture of white and very light grey coloured chalk which is soft and fine grained. The majority of the sediment is composed of coccoliths and their disintegration products. Foraminifera and calcispheres may form up to twenty five percent of the sediment. Non-carbonates form between 0.5% and 3% of the total
Light Grey Chalk:	Similar in composition to white chalk but containing up to 10% clay.
Calcarenitic Chalk:	Again, similar in composition to white chalk, but characterized by a large percentage of coarse shell debris.

Nodular Chalk: A unit of chalk which contains irregular cemented chalk nodules of variable hardness. The nodules are separated by softer chalk.

Chalkstone: A unit of chalk which is fully cemented. There is a complete gradation from white chalk through nodular chalk to chalkstone.

Intraclastic Chalk: Consists of intraclasts of hard, nodular chalk set in a softer (frequently calcarenitic) matrix.

1.3.3 Terminology and field classification of marly chalks

Marl is defined in the Collins English Dictionary as:

> "A fine-grained sedimentary rock consisting of clay minerals, calcium carbonate and silt."

In the Middle and Upper Chalk, the term 'marly chalk' is used to describe chalk which contains a higher than normal amount of non-carbonate material (usually between 10% and 35% in the Anglo-Paris Basin), clay minerals may form up to 75% of this. Because of the higher non-carbonate content it is frequently a darker colour, often brown, grey or green.

The terms marl band and marl seam are frequently intermixed and applied very loosely. Stratigraphers have used the terms to describe many different types of unit containing marly chalk. For the purposes of this work the following classification of marly chalk units will be used:

Flaser Chalk White, nodular or intraclastic chalk which has thin (usually less than 2 cm thick) streaks of marly chalk passing through it. Individual streaks are called flasers. Flaser chalks are believed to be formed during compaction of the sediment.

Flaser Marl: A laterally continuous unit containing thick flasers of marly chalk separated by lenses of white, nodular or intraclastic chalk. The marly chalk usually occupies between 10 and 40% of the total unit. It differs from flaser chalk because it is believed to be a primary

sedimentary feature, and laterally it may change into a marl seam.

Marl Seam: A discrete, usually laterally continuous, unit of near uniform marly chalk, usually between 1 cm and 20 cm thick. It may contain occasional white chalk intraclasts but these constitute less than 10% of the bed.

Marl Band: This name is used to define a complete, usually laterally continuous, unit containing marly chalk. It comprises the marl seam (or flaser marl) and any other associated beds containing marly chalk.

1.4 BRIEF HISTORY OF MARL BAND RESEARCH

Marl bands were first reported in the early part of the Nineteenth Century (Phillips, 1821). Whitaker (1865), was the first to observe that marl bands were laterally continuous over short distances, noting that "there is generally a thin layer of dark clay" a short distance above the Spurious Chalk Rock on the Isle of Wight. Sadly, Whitaker did not appreciate the possible value of this observation and, with the introduction of biostratigraphy, much of this early work was forgotten. Brydone's (1914) work on the lower Campanian in Sussex 'reintroduced' lithostratigraphy, noting that:

> "The minute lithological details correspond so closely that it can hardly be doubted that the marl beds, treated in the following section as corresponding, are actually continuous over the intervening areas."

and he concluded that:

> "The Zone of *O. pilula*...holds good in its broad features also for Sussex, the Isle of Wight and Dorset..., especially the way in which it ends in a bed 2'6" to 3' thick with a flint seam in the middle of it and enclosed by two marl seams."

Brydone was probably the first worker to realize that marl bands were both extensive, and of great value in correlation. He also made suggestions as to their origin, arguing that, because of their great lateral extent, it was unlikely that marl seams were originally composed of waterborne detrital material, rather that they represent airborne volcanic ashes. Later

work by Osbourne White (1921, 1926) showed that some marl bands within the Turonian were also correlateable over large distances, although their origin was not discussed.

Little further work was carried out on the origin of marl bands until Valeton (1959, 1960) and Dorn and Bräutigam (1959) gave details of volcanic tuff horizons within the German chalk. These horizons contain volcanic glass, clays (illite, kaolinite, illite/smectite and Fe-beidellite), feldspar, mica and heavy minerals (Seibertz and Vortisch, 1979), and have more recently been used in regional correlation of the Middle and Upper Turonian of northwestern Germany (Ernst *et al.*, 1983). There are, however, important compositional differences between the German tuff horizons and the marl bands of the Anglo-Paris Basin (see Chapter 8), and care must be taken when applying the German conclusions elsewhere. Nevertheless, a similar origin has been proposed for marl bands within the Chalk of Lincolnshire and Yorkshire (Pacey, 1984), and the Chalk of Kent (Robinson, 1984). Pacey (1984) based his proposal on the high smectite content of the marls, their anomalous trace element patterns, and the presence of volcanoclastic material.

In contrast, Jefferies (1963) suggested that current activity may be responsible for the formation of marl seams. Although dealing specifically with the Plenus Marl Formation (Cenomanian), he felt that his model of increased clastic input caused by river rejuvenation related to sea-level fall might be applicable to other marl seams as well. Alternative models for the genesis of the Plenus Marls are available elsewhere (Jarvis *et al.*, 1988a; Leary *et al.*, 1989). Robinson (1984) also suggested that current activity might be important in increasing the lateral extent of marl seams.

Recently, two authors have suggested that at least some of the German and English marls may be of secondary origin. Ernst (1978, 1982) proposed that marl bands may be formed through selective dissolution of calcium carbonate prior to burial. He carried out a quantitative analysis of foraminifera across a Maastrichtian marl band within the north German Chalk (marl layer M100), for which a volcanic origin had previously been proposed (Valeton, 1960). He found that the parameters studied (including planktonic/benthonic ratio, degree of corrosion and percentage of certain species) showed a systematic shift across the marl band which commenced some distance below it. He argued that his results showed a slow, but continuous, increase in the quantity of nutrients being introduced into the system, reaching a peak within the marl seam. The decomposition of the

organic matter increased the amount of carbon dioxide at the sediment-water interface, causing a lowering of the pH and an increase in calcium carbonate dissolution. A similar model has been proposed by Curry (1982) for marl seams within the English Chalk. These arguments have been questioned by Leary and Wray (1989), who show that the foraminifera variations may be related to palaeoenvironmental factors.

1.5 DISTRIBUTION OF MARL BANDS WITHIN THE ANGLO-PARIS BASIN AND LOCALITIES STUDIED

Any model discussing the formation of laterally extensive beds must first calculate their aerial extent. Almost all recent, detailed correlations involving marls have been undertaken in the northwestern part of the Anglo-Paris Basin and, although Mortimore and Pomerol (1987) have tentatively proposed that marls in the southeast of the Basin (the Yonne region) can be correlated with those in Sussex, correlation into inland France is difficult. Figure 1.1 illustrates the area within the Anglo-Paris Basin where marls can be correlated with some degree of confidence.

Most of the work contained within this thesis has been based on exposures in the northwestern part of the Basin, Figures 1.2 and 1.3 consist of maps showing the principal localities examined.

1.6 LITHSTRATIGRAPHIC SCHEME USED IN THIS STUDY.

1.6.1 History of chalk lithostratigraphy and the scheme used in this study

Much work has been done to try and divide the Chalk into smaller lithostratigraphic units. The first person to recognise any variation was probably the Reverend J. Townsend (1813) who noticed that the Chalk was composed of an upper white part and lower grey part, separated by a green rubbly unit (most probably the Chalk Rock). More detailed work commenced around 1818 with Mantell (1818) studying the Chalk in Sussex and Phillips (1821) studying the Chalk of the Kent coast. These workers concentrated on a lithostratigraphical subdivision chiefly based on the occurrence of flints, marls, organic remains and colouration. This work was

continued by Whitaker (1861, 1865, 1871a, b and c) and Whitaker *et al.* (1872).

Hébert's (1863, 1874) and Barrois' (1876) classic work on the zonal stratigraphy of the Chalk virtually ended the refinement of the then established lithostratigraphy. Their pioneering work heavily influenced the English workers of the time (Hill 1886; Rowe 1899, 1900, 1901, 1903, 1904, 1908; and Jukes-Browne and Hill 1903, 1904) to the extent that they all but dismissed lithostratigraphy in favour of biostratigraphy; for example Rowe (1908) considered Whitaker's work on the Isle of Wight to be of little value, describing it as "frankly pre-zonal". Despite the biostratigraphers' apparent contempt of the earlier lithostratigraphic schemes, much of their work made use of lithostratigraphical features to define biostratigraphical boundaries. The only notable exception to this trend was Brydone (1914) who recognised the wide extent of individual marl seams in the early Campanian of southern England (see Section 1.4).

In recent years a fresh attempt has been made to accurately define a lithostratigraphic framework for the Chalk. This work commenced with Jefferies' (1963) work on the Plenus Marls and continued with Kennedy (1969, 1970a) on the Cenomanian of southern England, Wood and Smith (1978) on the Northern Province Chalk of Yorkshire and Lincolnshire, Bromley and Gale (1982) on the Chalk Rock and Jarvis and Woodroof (1984) on the Cenomanian and early Turonian deposits of the Devon coast.

In 1983, Mortimore presented a proposed lithostratigraphic framework for the Chalk of Sussex, reinforced later by a more detailed paper (Mortimore, 1986a; see Figure 1.4). At the same time, Robinson (1986a) presented a detailed lithostratigraphic framework for the North Downs, in which he introduced a new set of names for the lithostratigraphical marker horizons. Whilst he noted marker horizon names used by earlier workers in the North Downs, he only established a correlation with one of the markers named by Mortimore (1983), despite the work of Bailey *et al.* (1984) which showed that it was possible to recognise many of the marker horizons in both areas.

In the same year, Mortimore and Wood (1986) proposed a detailed correlation between the upper Turonian chalk of Yorkshire and Lincolnshire (the Northern Province of England) and the Anglo-Paris Basin (the Southern Province), using the nomenclature of Mortimore (1986a). This correlation was made using a combination of marl seams (both their lithological

features and their geophysical characteristics) in association with a flint 'maxima' which they recognised in both provinces.

Mortimore and Pomerol (1987) expanded Mortimore's earlier scheme to encompass the whole of the Anglo-Paris Basin. They demonstrated that the marker horizons found in Sussex could be found across the whole of southern England (including Dorset, Devon, Hampshire and Kent), and also the French coast. They also attempted to correlate sections within inland France, but were hampered by insufficient exposure in some areas.

More recently, Quine (1988) produced a detailed lithostratigraphic scheme for the Haute Normandie Region of France. Because of the very different chalk facies found in this region (see Section 1.8.5), Quine produced yet another set of names (partly based on earlier local names). Although Mortimore and Pomerol's (1987) work had suggested tentative correlations between this region and the main part of the Anglo-Paris Basin, no attempt was made by Quine to integrate his scheme with this earlier work.

The separate issue concerning the grouping of marker beds into Members and Formations is also the subject of debate at the present time. Once again, Mortimore (1986a) and Robinson (1986a) produced two separate sets of names for the Chalk of southern England, the units usually having correlateable marker beds as boundaries. In addition to these schemes, additional names have been introduced for the Devon Chalk (Jarvis and Woodroof, 1984), Northern Province Chalk (Wood and Smith, 1978) and Haute Normandie Chalk (Quine, 1988). In an attempt to partly resolve this problem, Gale, Wood and Bromley (1987) produced a summary of the work carried out in southern England, and made recommendations as to a possible overall nomenclature (see Figure 1.5). Their recommended names are a combination of terms developed in Kent during the last century (Phillips, 1821; Dowker, 1870; Whitaker et al., 1872), and terms introduced in Sussex by Mortimore (1986a). Some of their suggestions were rejected by Mortimore (1988) who argued that:

> "on grounds of uncertainty, different lithological criteria and the incompleteness of the Kent sections with respect to the main 'Basin', the geographical names used by Phillips, Dowker, and Whitaker were inappropriate for the 'Basin' as a whole".

Despite (or perhaps because of) the large quantity of very detailed research which has been presented in recent years, there is still no one set of names for individual marker beds or groupings of them which is

universally accepted. For reasons of clarity and simplicity, this thesis will use Mortimore's (1986a) nomenclature for marker beds found in both the South and North Downs, and also for French sections (for the relationship between Mortimore's and Robinson's names in the Turonian and lower Coniacian see Figure 1.6). A further reason for this choice is that the South Downs sections are probably the most complete in the Basin, and contain units which are greatly condensed in the North Downs. Gale, Wood and Bromley's (1987) recommendations will be used with respect to the grouping of marker beds into Members, as their scheme encompasses the whole of southern England whilst retaining regional variations. Wood and Smith's (1978) nomenclature (with slight modifications from Wood *pers. comm.*) will be used for the Northern Province as the correlation between it and the South of England has yet to be conclusively proved. Bromley and Gale's (1982) nomenclature will be used for the Chalk Rock Member.

1.6.2 The Glynde Marls Complex

These Middle Turonian marls differ from all others in the succession as the number of bands can differ markedly between closely spaced exposures (a typical number is six, but up to twelve have been recorded by Robinson, 1986), and the correlation of many of the bands is uncertain. To avoid confusion when discussing these marls a system of roman numerals has been adopted for the numbering of marls at each locality, and will be followed by the name of the locality in square brackets []. The numerals only apply to the locality in question, and do not imply that a correlation between localities exists.

1.7 INTRODUCTION TO UPPER CRETACEOUS SEDIMENTATION IN THE ANGLO-PARIS BASIN

1.7.1 Hydrography

Several authors (for example Gordon, 1973; Tucholke and McCoy, 1986) have produced detailed maps of palaeoceanic current patterns in the Upper Cretaceous. All such reconstructions agree about the presence of a proto-Gulf Stream which flowed northeastwards along the western edge of the opening Atlantic. Quine (1988) suggested that this current produced the

large scale channels seen in Upper Turonian to Coniacian chalks in the western part of the English Channel and in the Haute Normandie Region of France. In eastern Europe a series of seaways allowed the mixing of Boreal and Tethyan waters (Gordon, 1973), and had the effect of removing many of the earlier faunal differences.

Apart from these gross considerations, much of our knowledge of water patterns in Europe is derived from faunal studies, using the assumption that water mass distribution was a major control of faunal patterns. Stokes (1971, 1975) has proposed three *Micraster* provinces for England and Northern France: Touraine-Aquitaine, Anglo-Paris and Northern England. The dividing lines between these provinces correspond with submerged massifs, implying that the latter may have influenced water patterns. It has also been shown that clear faunal similarities exist between the Northern Province of England, and Germany (Wood and Smith, 1978). In addition to these relatively fixed faunal provinces, it is possible to recognise 'pulse faunas' which are characteristic of one faunal province, but which occur briefly in another. An example of this is the presence of *Actinocamax plenus* in the Plenus Marl Formation of the Anglo-Paris Basin, as it is a species more characteristic of Central European and Russian (Boreal) waters (Jefferies, 1961). To date, no published work has described pulse faunas within the Turonian of the Anglo-Paris Basin.

1.7.2 Water depths and sea-level variations

The depth of the Chalk Sea was of great interest to many of the early workers, including: Hume (1894), Cayeux (1897) Jukes-Browne and Hill (1904). Many of these earlier workers based their proposals on similarities between Upper Cretaceous Chalk and recent deposits, arguing that either the Chalk was formed at a depth of several thousand metres, or that it was a very shallow water chemical precipitate (see Hancock, 1975a; p517). These early theories have been disproved, and it is generally believed that there are no recent deposits forming under the same conditions as Upper Cretaceous Chalks. Applying detailed palaeontological and palaeogeographical evidence, Hancock (1975a) concluded that white chalk was probably deposited in water between 100 and 600 m in depth, whilst Håkansson *et al.* (1974) suggested that much of the Maastrichtian chalk was deposited between 100 and 250 m.

The discovery of palaeo-shorelines, and detailed facies analysis, has shown that sea-level did not remain constant during the Upper Cretaceous. It is generally believed that these fluctuations were primarily eustatic (Kauffman, 1973; Hancock, 1975b; Naidin, 1971; Cooper, 1977; Hancock and Kauffman, 1979), possibly related to large scale tectonic activity (both oceanic and continental) due to seafloor spreading (Donovan and Jones, 1979), and also the elevation of the continents due to heat storage beneath them (Summerhayes, 1986). Some authors have questioned this idea (Yanshin, 1973; Hughes, 1976; Matsumoto, 1977), arguing that eustatic variations are highly over-rated, and that much more emphasis should be placed on local tectonic controls.

Hancock and Kauffman (1979; see also Hancock, 1989) produced a sea-level curve for the Upper Cretaceous of northwest Europe, which is in good agreement with the more recent global sea-level curves produced by Haq *et al.* (1988) (see Figure 1.7). There are several slight differences, probably the most important of which is the high number of short-lived regressions and transgressions on the Haq *et al.* curve which show marked departures from the long-term, smoother trend. Additionally, Haq *et al.* propose that much of the Santonian was regressive, whilst Hancock and Kauffman believe that much of it was transgressive, only becoming regressive in the late Santonian. For the remainder of this work Hancock and Kauffman's curve will be used, as it part-based on northwest Europe and may better reflect the sea-level variations in the Anglo-Paris Basin.

1.7.3 Sea-level Variations During the Turonian

From Hancock and Kauffman's (1979) curve it is apparent that sea-levels were at a maximum towards the base of the Middle Turonian, sea-levels then fell, reaching a minimum in the Upper Turonian before rising again. Sea-level fluctuations around the Cenomanian-Turonian boundary are more difficult to interpret. Jefferies' (1963) interpretation of the Plenus Marls (Upper Cenomanian) was that it reflects a sudden, brief regression; whilst Jarvis *et al.* (1988a) argued that the Plenus Marls represents a rapid transgression, which then continued at a slower pace in the Lower Turonian. Hancock and Kauffman's sea-level curve shows a sharp regression towards the top of the Cenomanian, but not enough detail is given to confirm that it corresponds with the Plenus Marls. Haq *et al.*'s curve differs slightly, suggesting that the major regression took place in the Middle Cenomanian, with a brief, subsequent regression towards the middle

of the Upper Cenomanian. Gale (*pers. comm.*) suggests that a combination of these interpretations is probably correct: the base of the Plenus Marls is probably regressive (with a locally developed hardground), but the upper beds are probably transgressive, as is the Melbourne Rock.

In the Touraine region, the upwards transformation from marly chalks to calcarenites rich in coarse grained detritus suggests that, for much of the Turonian, sea-levels were falling (Jarvis and Gale, 1984). This same pattern is repeated in the Aquitaine Basin, south of the Armorican Massif-Central Massif divide. Here, the succession has been interpreted as reflecting rapid subsidence at the start of the Turonian, followed by gradual filling without further downwarping (Cassoudebat and Platel, 1976).

1.8 TURONIAN PALAEOGEOGRAPHY OF THE ANGLO-PARIS BASIN

1.8.1 Introduction

By the start of the Turonian much of Western Europe was submerged, only small, isolated islands (of land) remained (see Figure 1.8). Consequently the amount of clastic material being deposited was markedly reduced, resulting in the deposition of white chalk. Emerged massifs, structural highs and tectonic activity affected many of the more marginal areas, causing fluctuations in the rate of deposition and the percentage of non-carbonate material.

The Anglo-Paris Basin is bounded to the north and east by the London-Brabant Massif and Mid-European High. To the south and west it is bounded by the Massif Central and the Armorican Massif. The following Sections describe the facies seen within the Basin, and attempts to reconstruct their depositional environment.

1.8.2 Central Basin Facies

Within deeper parts of the Basin (as typified by the sections in Sussex), the Lower Turonian consists of slightly nodular, calcarenitic chalk with frequent, often flaserish, marl bands. The calcarenitic material consists of fragments of brachiopods, bivalves (especially inoceramids) and other

elements of the macrofauna. These beds probably reflect deposition in relatively shallow water, influenced by comparatively high current activity.

The lower half of the Middle Turonian typically consists of more massive fine grained chalks, and contains thick, prominent marl bands (for example the New Pit Marls). Thick marls are also a characteristic of the higher parts of the Middle Turonian, but the chalk is frequently nodular and often contains flints. The soft, massive nature of the chalk suggests that deposition occurred in relatively deep water, without the high current activity found in the Lower Turonian.

The Upper Turonian is characterised by prominent nodular units (for example the Kingston Nodular Beds of Mortimore, 1986a), and well defined marl bands (for example the Bridgewick Marls). Also found at this level are a number of distinctive flint bands (for example the Bopeep Flints), which have been used by Mortimore and Wood (1986) in an attempt to correlate between the south of England and Lincolnshire. The formation of nodular units is often associated with an increase in current speed. In the Upper Turonian this is likely to be the result of eustatic sea-level fall (see Sections 1.8.1, 2.7 and 2.8.2a).

1.8.3 Facies close to a submerged massif

The cliff sections either side of Dover show some stratigraphic differences in facies when compared to Sussex. The Lower Turonian is much more condensed: the lower half consists of calcarenitic nodules and pebbly intraclasts, set in a calcarenitic matrix; whilst the upper half consists of nodular units. The Upper Turonian is also more condensed, illustrated by the cutting out of the Lewes Marl on the Dover Chalk Rock (*sensu* Stokes, 1975) hardground. In contrast, the Middle Turonian consists of soft white chalk, part of which (between the Glynde and Southerham Marls) is thicker than the 'basinal' sections in Sussex. These fluctuations are probably due to weak tectonic activity associated with the nearby London-Brabant Massif.

1.8.4 Facies over a submerged massif

The London-Brabant Massif was probably submerged by Cenomanian times, but it remained as a topographic high for much of the Turonian. The late Turonian fall in sea-level affected sedimentation over the Massif, and resulted in the formation of a series of indurated hardgrounds known

collectively as the Chalk Rock. This unit consists of a series of glauconitised and phosphatized hardgrounds, below which there is usually a unit of fully cemented chalk (termed chalkstone by Bromley and Gale, 1982). The period of time represented by these hardgrounds, and their correlation with the main part of the Basin, has been debated for some time. Data acquired during the preparation of this thesis suggests that all the Upper Turonian and part of the Middle Turonian may be represented by these surfaces (see Chapter 7).

1.8.5 Facies in a region of high current activity

Cliff sections in the Haute Normandie region of France show numerous channel and scour structures (Quine, 1988), which may be up to 65 m in height and 1000 m in width. Although facies relationships are complex, the walls and floor of the channels consist of either nodular chalk or chalkstone; whilst the channel fill is usually seen to fine upwards, commencing with wackestones and terminating with mudstones. Geophysical profiles have shown that these structures are present across much of the English Channel. Quine (1988) proposed that these features were caused by the proto-Gulf Stream as it entered the Anglo-Paris Basin. The presence of local tectonic highs (Armorica and Cornubia) appear to have controlled the distribution pattern of the channels and scours. Field relationships suggest that some small-scale scours and channels were formed during the Lower to Middle Turonian, but large scale channeling did not commence until the Middle to Upper Turonian.

1.8.6 Facies in a regressive near-shore environment .

In the Touraine region (east of the Armorican Massif), the Lower Turonian consists of marly chalk which, at the base of the Middle Turonian, passes quickly into micaceous calcarenite (termed 'Tuffeau blanc'). The Upper Turonian (Tuffeau jaune) is again calcarenitic, but there is little or no mica, and quartz is the dominant detrital phase. Units rich in glauconite may also be present, especially towards the top (Robaszynski [Coordinator], 1982). Riveline-Bauer (1965) noted that smectite and illite are the two dominant clay minerals, the proportion of illite increases upwards, and in the Upper Turonian kaolinite is occasionally present in trace amounts. The association of the above features strongly suggest that the sea was regressive for much of the Turonian in this region. The Turonian is

overlain by the disconformable and transgressive Craie de Villedieu Formation of Lower Coniacian age (Jarvis and Gale, 1984).

1.8.7 Facies adjacent to an emerged massif

The Mons Basin is a offshoot of the Anglo-Paris Basin and is situated adjacent to the Ardennes, which was not fully submerged for much of the Upper Cretaceous. The Lower and Middle Turonian consists of calcareous sediments which contain up to 50% clastic material (Godfriaux and Robaszynski, 1969). In contrast, the Upper Turonian contains no more than 10% clastic material. The Lower and Middle Turonian sediments (termed "Diéves") contains kaolinite (10-15%), smectite (10-15%) and Illite (10-30%); the Upper Turonian contains no kaolinite, and more smectite than illite. The lateral extent of this facies is a little unclear, but Robaszynski (1981) suggested that it extended as far south as the Somme in the early Turonian, and it has been proved in a borehole at Loffre, near Douai (Robaszynski and Amédro, 1986).

The clastic material is believed to have originated from two sources. Some material was probably derived from the adjacent Massif which, for much of the Turonian, was being transgressed by the Chalk. The material derived from the Ardennes may not however have been the most important source. A study by Godfriaux and Robaszynski (1969) showed that the mineralogy of the Diéves is different to that of the Palaeozoic rocks of the Massif. They suggested that a more likely source for much of the material was from Lower Cretaceous sediments (Wealden and Albian), which the Upper Cretaceous sediments overstep.

1.8.8 Facies in a tectonically active region

In southeast Devon, outliers of Cenomanian and Turonian age contain numerous hardgrounds and units of nodular chalk. The sediments show marked lateral variation in thickness over short distances. Jarvis and Woodroof (1984), showed that the Lower Turonian is condensed from 13.6 m to 0 m over a distance of 2.25 km, whilst the lower part of the Middle Turonian varies from 18.5 m to 10.85 m over a distance of 1.6 km. Smith (1957a, b, 1961, 1965) suggested that these variations were caused by intra-Cretaceous folding. Jarvis and Woodroof (1984) disagreed with this

suggestion, and proposed instead a model based on the syndepositional movement of underlying fault blocks.

2. SEDIMENTOLOGY AND DIAGENESIS

2.1 SUMMARY

The aim of this Chapter is to study marl band sedimentology and diagenesis and to compare it to other clay-rich features found within chalks.

Marl bands are shown to be primary features of the Chalk which do not occur on a regular basis and seem to be associated with eustatic sea level regressions. A classification scheme for marl bands is proposed based on field characteristics, and divides marl bands into two main types: those containing a single, thick marl seam, and those containing numerous, thin interwoven flasers (a flaser marl). They are found overlying the full range of chalk lithologies, from white chalks to hardgrounds. Marl seams usually have a sharp, well defined base and a gradational top, whilst flaser marls have a gradational top and base. A more clay-rich layer usually occurs 2-3 cm above the base of a marl seam and this is interpreted as representing the sediment-water interface at the commencement of formation, the base of the seam being a reflection of the depth to which complete bioturbation extended. Burrows infilled with marly chalk are observed passing upwards and downwards from the marl seam or flaser marl, whilst occasional burrows infilled with white chalk occur within marl seams.

A model for their formation is presented which proposes that marl bands containing marl seams were formed by a sudden sharp increase in non-carbonate sedimentation, whilst carbonate sedimentation continued unaffected. A model for flaser marl formation proposes that they were formed in more than one way, but the most likely are either: intermittent deposition of non-carbonate-rich sediment, or a decrease in the amount of non-carbonate sediment deposited. The final form of both types of marl band is heavily influenced by the amount of post-depositional bioturbation that they underwent.

Compaction during burial results in most burrows above and below marls being transformed into thick flasers, similar to those associated with omission surfaces. Compaction and dewatering has also resulted in deformation of marl seams and any white burrows contained within them.

A study of omission and erosion surfaces shows that they are primary features of the Chalk which, unlike marl bands, occur rhythmically with a

spacing of between 0.2 and 2 m. They are believed to have been formed as a result of a break or marked decrease in the amount of carbonate sedimentation. Cementation of chalks underlying the surface can be used as a guide to the length of time that the surface was exposed for. The chalk overlying omission surfaces is usually more clay-rich than that underlying it, implying that non-carbonate deposition continued unaffected; chalk overlying erosion surfaces may or may not be more clay-rich, depending on the point at which erosion stopped. Omission surfaces do not represent the actual palaeo-sediment/water interface, but rather that point in the sediment column where complete bioturbation stopped when the more clay-rich chalk was deposited. The fining upwards nature of chalks overlying erosion surfaces is attributed to bioturbating organisms continuously reworking upwards the coarse basal lag developed on the surface whilst it was exposed. A model for the formation of omission and erosion surfaces is presented, along with a classification scheme.

Flasers and flaser chalks are diagenetic features developed within easily deformed, relatively clay-rich chalks by pressure solution during burial. Their position relative to primary omission and erosion surfaces is controlled by the degree of post-depositional cementation of the chalk. Where cementation of the chalk below the surface is negligible flasers are smooth and sub-horizontal, occurring within *Thalassinoides* burrow systems. Where well developed nodules are present, irregular flasers occur on the surface and within *Thalassinoides* burrows beneath it, becoming more deformed as nodularity increases. If nodules have coalesced to form a network, or when a chalkstone is developed, flasers occur in the more clay-rich chalk above the surface but are prevented from forming beneath it by the rigidity of the cemented units.

2.2 GENERAL INTRODUCTION

2.2.1 Chalk sedimentation

Coccoliths live almost exclusively in near-surface waters and, until recently, it was believed that after death they slowly sank to the bottom hindered only by slight current activity (Hancock, 1975a; Reid, 1973). Calculations by Clayton (1984) suggest that, under calm conditions, a coccosphere would take 60 days to fall 200 m, whilst a coccolith disc would take 9 months.

Recent work by Jarvis (1980a), Robinson (1984, 1986b) and Quine (1988) has shown that current activity was widespread within the Chalk Sea, suggesting that that it would be difficult for coccoliths to settle on the sea-floor unaided. Schrader (1971) and Pryor (1975) have shown that the sedimentation of fine detritus is greatly speeded up if the material passes through the digestive system of a copepod or other filter feeder, being eventually ejected as a larger faecal pellet which would sink at a much quicker rate. Hattin (1975) has described such pellets from the Upper Cretaceous of North America, and it seems likely that a mechanism similar to this was responsible for the deposition of much of the European Chalk. Evidence to support this process in the Chalk is rare, as the deposited pellets would have quickly been broken down by physical reworking and bacterial action. Nevertheless, loosely packed pelletal chalk is occasionally found in burrows, and phosphates commonly occur in the form of faecal pellets (Jarvis 1980a).

2.2.2 Rates of deposition

Calculated rates of deposition depend to a great extent on the period of time involved: the greater the time length, the slower the rate of deposition because of the increased number of depositional breaks, this is further complicated by the degree of compaction which the sediment has undergone. Scholle (1977) argued that on deposition a typical chalk 'ooze' will have a porosity of between 70 and 80%, whilst after compaction typical porosities range between 35 and 50%. As most depositional rates are calculated by dividing a thickness of chalk by time, they represent the 'compacted' depositional rate rather than the true sedimentation rate. Assuming a duration for the Turonian of 3 Ma. (Haq *et al.*, 1988) the following 'compacted' depositional rates can be produced:

Location	'Compacted' rate (cm/1000yrs.)
Beachy Head (Sussex)	4.4
Dover (Kent)	2.9

Chalk at Beachy Head and Dover has been compacted by a similar amount, the difference in the calculated rate reflecting the condensation found in the Lower and Upper Turonian at Dover. These figures are in good agreement with those produced by Hancock (1975a) for the Turonian, but are much lower than those calculated by Håkansson *et al.* (1974) for the

Maastrichtian of Denmark 15 cm/1000yrs) which apparently shows few depositional breaks.

2.2.3 Bottom conditions

The silt to clay grade nature of white chalk poses a problem when trying to establish its mechanical properties. In the past, workers produced models based on faunal evidence (see Kennedy and Garrison, 1975), arguing that many bivalves and brachiopods have adaptive features (for example spines and frills; Carter 1968, 1972) which imply a very soft, almost soupy bottom. Recently, some authors (Gale and Smith, 1982; Gale, 1984) have questioned these ideas, arguing that: a similar fauna is found on hardgrounds; adaptive features found on echinoids suggest a firm substrate just below the surface; and the presence of minute suspension feeding brachiopods necessitates a firm substrate. The preservation of numerous burrow systems (notably *Thalassinoides*) also suggests that a short distance below the surface the sediment was firm.

Comparisons have also been made with Recent muddy sediments described by Rhoads (1970, 1973) and Rhoads and Young (1970), which show thixotropic properties. An important difference between these sediments and white chalk is the proportion of clay minerals present, as this drastically affects the physical properties of the material. Clay minerals are electrically charged and have a platy form, giving rise to two distinctive characteristics: they flocculate easily, and they can retain a film of water on their surfaces (Burst, 1976; Newman, 1987). The combination of these features allows clays to naturally form a slurry when placed in water and enables a clay-rich sediment to have thixotropic properties. As clays only constitute 1 or 2% of white chalk it is very unlikely that they would have a major effect on the properties of the sediment. Because calcite does not have the same properties as clay minerals, it is far more likely that freshly deposited white chalk behaved like a fine silt, dewatering and quickly becoming firm. The behaviour of marly chalk is more difficult to assess as its properties will greatly depend on the amount of clay present: the higher the percentage, the more thixotropic the material will be. This contrast between white and marly chalks is very important and can be used to explain many of the features seen in Upper Cretaceous chalks (see Sections 2.8, 2.9 and 2.10).

There is abundant evidence for winnowing within the Chalk: calcarenitic material is often found infilling burrows on hardgrounds (Robinson, 1986b); and at certain horizons, for example the Melbourne Rock, coarse bioclastic material occupies an unusually high proportion of the sediment. The current speed necessary for winnowing is difficult to assess, but to lift material a unidirectional current needs a speed of between 1 and 50 cm/sec depending on the proportion of clay within the sediment (Sundborg, 1956). However, an oscillating wave current may aid the process by suspending the sediment, which would then require only a weak unidirectional current to transport it (Komar, 1976).

Hard substrates (hardgrounds) have been documented at many levels within the Chalk, and may be laterally continuous over large areas (Bromley and Gale, 1982). Their formation is probably related to a combination of non-deposition and increasing current velocities (see Section 2.7). They are frequently mineralized and have a characteristic fauna including: encrusting bivalves, corals, gastropods and borings (Bromley, 1965, 1975; Kennedy and Garrison 1975). Cementation within chalk is discussed further in Section 2.8.2

2.3 BIOTURBATION AND ICHNOLOGY

2.3.1 Introduction

Bioturbation was probably the most important post-depositional process affecting the Chalk. Because of the fine grained nature of chalk, evidence of bioturbation is usually only seen where there is a colour contrast between the burrow infill and the surrounding chalk, or where diagenetic processes have altered the original sediment (for example, flint replacement of burrow-fill chalk).

Bioturbation was first noted in the Chalk by Webster (1814), and detailed studies commenced in the 1940's and 1950's (Ellenberger, 1946, 1947; Cayeux, 1950; Voigt and Häntzschel, 1956; Voigt, 1959). The subject was 'revived' by Bromley (1967a) and Kennedy (1967), the former presenting a paper on observations on burrows of thalassinidean Crustacea in chalk hardgrounds and the latter producing a classification of trace fossils within the Lower Chalk. These papers rekindled interest in chalk ichnology

and, along with subsequent papers (Bromley 1968, 1975; Kennedy 1970b, 1975; Nygaard, 1982a and b; Bromley and Ekdale 1984a, 1984b, 1986a; Ekdale and Bromley 1983, 1984a, 1984b, 1984c; and Ekdale, Bromley and Pemberton 1984), have produced a much clearer picture of bioturbation within chalk; a summary of this work is presented below.

2.3.2 Trace fossil associations in Upper Cretaceous chalks

Trace fossils most commonly found in chalks include *Thalassinoides, Zoophycos, Chondrites, Planolites, Bathichnus* and *Trichichnus*. Although these are all relatively deep burrowing forms, it is possible to show tiering based on cross-cutting relationships, sediment infill and burrow preservation (see Figure 2.1).

Analysis of trace fossil associations at omission surfaces allows the recognition of three different assemblages: the preomission suite, the omission suite and the postomission suite. The preomission suite, formed before the development of the omission surface, generally consists of feint burrows, and is truncated by the omission surface. The omission suite, produced during the formation of the omission surface, can differ in form and composition from the preomission suite because of the environmental change which caused the formation of the surface. Thus, it may contain new ichnospecies, and preservational differences if the omission surface is exposed for a long time (omission suites associated with hardgrounds frequently have mineralized walls). The omission suite occasionally contains sediments unrepresented elsewhere at the omission surface, as sediments produced at the time of omission will have preferentially infilled the burrows and avoided later reworking. The postomission suite, formed after the recommencement of deposition, may cross-cut the earlier suites or re-excavate the omission suite burrows - a controlling factor being the degree of lithification of the omission surface. Bromley (1975) noted that whilst the pre- and postomission suites found in the Chalk consist of a mixed ichnofauna (*Thalassinoides, Chondrites and Zoophycos*), the omission suite consists only of *Thalassinoides*.

Some trace fossils give information concerning environmental conditions. For example, *Bathichnus* is frequently, although not exclusively, found in rapidly deposited or redeposited chalks; whilst *Trichichnus* often reflects the escape of an organism from sudden overburden. In contrast, *Chondrites*

and *Zoophycos* suggest stable and quiet conditions, and possibly slight anoxia, within the sediment.

2.3.3 Trace fossils in Recent pelagic sediments

Studies of bioturbation in recent pelagic calcareous oozes greatly assist in the interpretation of the Chalk. Berger *et al.* (1979) examined a series of box cores from the equatorial Pacific and found that it was possible to divide the near-surface sediment into three layers based on burrow preservation (see Figure 2.2). They found that for up to 7 cm below the sediment-water interface (termed the mixed layer) the sediment was totally bioturbated, but no record of this bioturbation was preserved. For preservation to occur, the burrowing organism must pass through the mixed layer and enter the layer below (termed the transition zone), which is composed of firmer sediment buried deep enough to avoid complete reworking. The upper boundary of this layer is gradational, and an additional unit (the mixed layer transition), in which only partial preservation occurs, can sometimes be seen. At the lower limit of bioturbation the sediment passes into the historical layer. Berger *et al.* (1979) found that burrow preservation within the historical layer deteriorated into a series of "mottles", although evidence from Deep Sea Drilling Program (DSDP) cores has shown good preservation of trace fossils at great depths within the sediment, suggesting that lithification may enhance ichnofabrics.

As it is likely that similar preservation conditions occurred in the Chalk Sea, the above helps to explain the lack of evidence of shallow burrowing organisms (for example echinoids), as their traces would be obliterated through subsequent sediment reworking.

Berger *et al.*'s (1979) ideas are also very important when considering omission surfaces and changes in the composition of the sediment, these are discussed in the following Sections.

2.4 MARL BANDS

2.4.1 Introduction

The term 'marl band' is used in this work as a general name, covering flaser marls, marl seams and their associated marl-rich units. Although marl bands have been used extensively in recent lithostratigraphic studies, and have been noted in scientific papers for over a century, there has been little investigation of their sedimentology or relationship with the chalk above and below. Previous workers who have discussed marl bands (including: Garrison and Kennedy, 1977; Mortimore, 1979, 1986a and b; and Robinson, 1984) have concentrated on a few examples within small areas, and consequently have omitted or misinterpreted many important features. Detailed field descriptions of marl bands found in the Middle and Upper Turonian can be found in Appendix 2, and it is upon these marls that much of the following work is based. Many of the descriptions are from coastal exposures, their fresh and often wave-washed nature provides much detail which cannot be easily seen on inland, weathered sections. The appendix also contains descriptions of most of the marls found at other stratigraphic levels.

The object of this Section is to examine and discuss the features seen in the field, and to hopefully improve the sedimentological knowledge of marl bands. Although there is a great deal of common ground, marl seams and flaser marls will be discussed in separate Sections.

2.4.2 Stratigraphic variation

The work of Bailey *et al.* (1983, 1984) and Mortimore and Pomerol (1987) has shown that many marl bands are laterally continuous features which can be traced over a large part of the Anglo-Paris Basin. In addition, the detailed sedimentary logging of Mortimore (1983, 1986a), Robinson (1986a) and Mortimore and Pomerol (1987) has shown that marl bands do not occur continuously throughout the succession.

Probably the best region to study stratigraphic variations is Sussex, as it has the most complete exposed succession in the Basin. The section seen at Whitecliff on the Isle of Wight is also included as it contains sediments younger than those seen in Sussex. When discussing stratigraphic variation some care should be exercised, parts of the succession seen in Sussex do

not qutcrop, or are poorly exposed, in other parts of the Basin; hence there may be significant regional variations which have not yet been detected.

Figure 1.4 shows the stratigraphic distribution of marl bands using data from Sussex and the Isle of Wight, it shows clearly that marl bands are not found throughout the whole of the Chalk, and, at certain horizons (upper Middle Coniacian to upper Middle Santonian, and Middle Campanian) no marl bands are found. Marl seam distribution in the North Downs is similar for most of the succession, but they are absent in the Lower Turonian and the Upper Santonian to Lower Campanian. Whilst in the Lower Turonian this is probably related to condensation of the sediment at this locality (see Section 1.8.3), their absence in the highest part of the succession is difficult to explain.

Plotting the stratigraphic variation against the sea-level curve of Hancock and Kauffman (1979) (see Figure 2.3) shows that the marl band maxima tend to coincide with falls in sea-level. Conversely, rises in sea-level tend to be associated with the development of few or no marl bands. Considering the relatively few data points on Hancock and Kauffman's (1979) sea-level curve, the fit of the marl band data is remarkable, if not perfect. Importantly, the pattern adds support to the suggestion by Jefferies (1963), that marls may be formed as a result of river rejuvenation caused by a fall in sea-level. The one exception to this simple trend is found in the Lower Turonian, where marl bands are found during what is believed to be a major transgression.

2.4.3 The effect of condensation on marl bands

The Upper Turonian eustatic sea level fall resulted in condensation of much of the Chalk in the south of England, and gave rise to the Chalk Rock hardgrounds over the London Platform-Mendip High (see Bromley and Gale, 1982). Marl bands are found in all but the most condensed parts of the Basin, but may be slightly thinned or deformed by the presence of nodules within the sediment (e.g. the Bridgewick Marls at Dover). Within the Chalk Rock, marl bands occur, but become 'cut out' on hardgrounds in the more condensed parts. (see Bromley and Gale, 1982).

2.4.4 Marl band classification

In order to simplify many of the descriptions found in Appendix 2 and the following Sections, a simple classification has been created which divides marl bands into six types based on their appearance in the field (see Figure 2.4):

Type A: A marl band consisting of a marl seam (of variable thickness) which has white chalk above and below it. Flasers pass both upwards and downwards from the marl seam.

Type B: A marl band similar to a type A but the marl seam rests on a well defined omission (or erosion) surface. The chalk below the surface is often nodular. Flasers of varying thickness pass up from the marl seam and pass down from it into the nodular unit.

Type C: A marl band which contains a flaser marl. The chalk which separates the flasers is white and soft, or very weakly nodular. The upper and lower boundaries of the unit are where the flasers grade into the white chalk above and below.

Type D: A marl band similar to a type C but the chalk separating the flasers is nodular.

Type E: A marl band which is similar to a type C but the flaser marl is seen to rest on a prominent omission (or erosion) surface. The chalk below the surface is usually nodular.

Type F: A marl band similar to a type D but with a prominent omission (or erosion) surface underlying the flaser marl.

A marl band may display more than one element of the classification. For example: a type A/C marl would be one which has a marl seam which is slightly flasered.

2.5 MARL BANDS CONTAINING MARL SEAMS

2.5.1 Introduction

Of the two types of marl band, ones containing marl seams (types A and B) are the most easily distinguished in the field; on coastal exposures their presence produces notches and 'benches' in the cliff-line, whilst inland on weathered exposures their position is often defined by a stripe of vegetation. The following discussion is divided into Sections discussing the sedimentary and bioturbational features; their diagenetic alteration is discused in Sections 2.8 and 2.10.

2.5.2 Sedimentary features

a) Lower contact with the white chalk

The nature of the lower contact between a marl seam and white chalk is very variable, and can exhibit many of the features seen on omission and erosion surfaces. Because of the change in sediment composition, a marl seam produces, by default, an 'omission surface', and in many cases it is very difficult to determine if there is a break in sedimentation associated with its formation. Examples of marl seams which overly soft white chalk include New Pit Marl 1 (Caburn Pit, Sussex), New Pit Marl 2 (Puys, France) and Southerham Marl 1 (Eletot, France; Plate 1a).

Numerous marl seams (including: New Pit Marl 2 and Southerham Marl 1 (Caburn Pit, Sussex), and Bridgewick Marls 1 and 2 (Langdon Stairs, Dover and Bridgwick Pit, Sussex)) can be seen to overly nodular surfaces. There is little or no evidence of erosion or exposure associated with these surfaces, and hence they are best classified as omission, rather than erosion, surfaces. New Pit Marl 2 at Akers Steps (Dover) and Beachy Head (Eastbourne) differs from this generalization: at both localities, the marl seam overlies, and passes between, an intraclastic conglomerate composed of nodular white chalk (Plate 1b). The hardness of the intraclasts differs between the two exposures, those at Akers Steps are harder, and presumably better cemented than those at Beachy Head. This feature, although striking when seen in the field, cannot be described as diagnostic of the Marl because in other sections both close to Beachy Head (Caburn Pit and New Pit), and further afield (Puys, France) it is not seen; indeed, even within the relatively short exposure seen at Beachy Head, the

thickness of the intraclastic unit varies markedly. It is likely therefore that the intraclasts were formed as a result of localised channeling (see Robinson, 1984) related to fluctuations in current speed.

Only one marl (Marl IV, Burghclere) has been found resting on a mineralized hardground.

b) Marly chalk

The marly chalk which makes up the marl seam is of variable colour and texture. When wave-washed and fresh, marly chalk is usually a medium to dark grey colour, weathering tends to lighten the colour and turn it slightly brown. The most probable cause of this transformation is the oxidation of fine-grained disseminated pyrite often found in marly chalk (see Mineralogy), producing yellow-brown limonite. Marls found close to the top of a section are often a very light grey colour, suggesting that they may have been partially leached by downwards percolating meteoric waters. White chalk intraclasts are occasionally found within marl seams, these are usually hard, with sharp edges, and are often derived from underlying nodular or intraclastic chalks.

Texturally, marly chalk varies from firm and brittle, to soft and plastic. Part of this variation is undoubtedly due to weathering, as prolonged exposure of marly chalk results in the evaporation of at least part of the water held by the clays, producing a much more brittle material. Wave-washed exposures of marly chalk show that it is firm, but softer than adjacent white chalk. Many of the thicker marls exposed on the coast show a similar, vertical textural variation: at the base of the seam the marly chalk is firm, but 2-3 cm above it is transformed, becoming softer and more plastic. The softer chalk is usually only 1-2 cm thick and grades gradually back to a firm marly chalk similar to that found at the base of the seam. Assuming that the softness and plasticity of fresh marly chalk is directly related to the percentage of clay present within it, the above observations indicate that the percentage of clay fluctuates as a marl seam is traversed. This trend may be a primary feature which has been modified by bioturbation, or it may be a result of pressure solution during burial. Both these possibilities are discussed in subsequent Sections.

Glynde Marl I [Caburn, New Pit, Beachy Head] differs texturally from all others in the Anglo-Paris Basin; its probable equivalents at Akers Steps (Dover) and at Puys (France) display slightly similar features, but they are

not as well developed. Although thin (usually about 3 cm in thickness), this marl is easily recognised in the field because of its' very dark grey and plastic marly chalk; even when affected by weathering this diagnostic feature is usually preserved. Careful examination shows that the marly chalk at the top and bottom of the marl seam is much firmer than that found in the centre. The reason for the marked difference between this marl and others in the Anglo-Paris Basin is difficult to explain at this stage but, if the marly chalk is of primary origin, it may be due to a variation in the rate of bioturbation, or a variation in the sedimentation rate; this problem is discussed further in subsequent Sections.

Mortimore (1979, 1986a) noted that the marly chalk of the Lewes Marl is coarser than the white chalk above and below it. This may be related to the presence, directly below it, of an iron-stained nodular unit. If this unit represents the formation of an incipient hardground, winnowed material from its surface may have become mixed with the marly chalk through bioturbation.

c) Upper contact with the white chalk

Generally speaking, marl seams grade quickly into the overlying white chalk. The contact is not usually as sharp as that seen at the base of the seam, and flasering may occur (see below). New Pit Marl 2 at Beachy Head is unusual because, in places, the upper contact is very sharp and has a thin calcarenitic unit separating the white and marly chalks. The best explanation for this feature is that the calcarenitic unit is derived from gentle winnowing of the upper part of the marl seam.

2.5.3 Bioturbation features

a) Below the marl seam

In the white chalk below marl seams there is abundant evidence of bioturbation. Well defined, compacted burrows composed of marly chalk are often seen extending from the marl seam to a depth of 20 cm, whilst occasional isolated flasers of marly chalk may occur to a depth of 60 cm. Although subsequently deformed during compaction, the pattern of burrows and flasers is often similar to the burrow system produced by *Thalassinoides* (see Section 2.3.2). Compacted burrows adjacent to the seam may be up to 4 cm thick and similar in colour to the marly chalk above,

passing downwards they become thinner and lighter in colour. Although rare, burrows and flasers can be observed which show some evidence of subsequent reworking by *Chondrites*.

Occasionally, well preserved burrows can be seen below marl seams. Some of the best examples of this can be seen below New Pit Marl 2 at Beachy Head (Plate 4a), where erosion has produced a broad step in the white chalk directly below the marl seam, giving a plan view of the sub-marl surface. Well defined burrows with a maximum vertical range of 20 cm are seen extending through the intraclastic conglomerate below the marl and passing into the white chalk below. The burrows are a maximum of 5 cm in diameter and occasionally branch, and are best classified as thalassinidean. The fill of the burrows is complex, consisting of coarse, medium grey marly chalk with occasional streaks of darker, more clay-rich material. The colour of most of the material is similar to that of the marly chalk above. Also contained within the burrows are white chalk pebbles derived from the overlying intraclastic unit. A plan view of one of these burrows shows it to have been reworked, and the burrows infilled with white chalk. The presence and preservation style of the latter indicates that burrowing organisms were capable of passing through the marl seam and reworking the burrows below it. Evidence of burrows passing through the overlying marl seam is very limited at this locality, although internal deformation of the marl seam during subsequent de-watering may well have hindered their preservation.

b) Within the marl seam

Occasionally, white-chalk-filled burrows (? *Planolites* or *Thalassinoides*) are found within marl seams, usually close to the top (examples include New Pit Marl 2 at Puys, and a Coniacian marl on the foreshore to the south of Fecamp [termed the Fecamp Marl by Gale *pers. comm.*] - see Plates 4b and 5a). They tend only to be present in marl seams with more gradational upper contacts, and are almost certainly a product of burrowers entering the marl seam from above. The fact that the burrows are preferentially infilled with white rather than marly chalk implies that the marly chalk was both sufficiently firm to support the burrow and, that the relatively dilute marly chalk through which the burrow passed was further diluted and lost much of its original identity if incorporated into the burrow-fill. Examples are occasionally seen of white-chalk filled burrows which contain a marly chalk centre (Plate 5b). Although there are several possibilities for

their genesis, they are most likely to have been formed by an organism reworking the white-chalk filled burrow and extending it into the marly chalk, some of which the organism subsequently transported back into the burrow.

Bioturbation similar to that described from the Kjølby Gaard Marl in Denmark (Ekdale and Bromley, 1983) is not usually found within the Anglo-Paris Basin. This may be due to variations in the palaeoceanic conditions at the time of deposition of this marl, and preservational differences related to factors such as the amount of compaction.

Variations in the proportion of clay within the marly chalk (as discussed in Section 2.5.2b above) may be related to the bioturbation history of the marl. If the mixed layer-transition zone-historical layer model of Berger and Heath (1968) and Berger *et al.* (1979) is applied to marl seams (Section 2.3.3), an explanation for the pattern can be derived. Assuming that, prior to the deposition of the marly chalk, the upper few centimetres of the white chalk were being continuously reworked by the bottom dwelling fauna, the boundary between the white chalk and the marly chalk would define the mixed layer-transition zone boundary, rather than the 'palaeo'sediment-water interface. If the change in conditions which gave rise to the deposition of the clay-rich chalk was fairly rapid it is unlikely that the organisms within the mixed zone would be able to completely homogenise the sediment, and therefore the level at which the clay-rich chalk was introduced would be at least slightly richer in clay that the sediments above and below it. By the same token, the point at which the deposition of clay-rich chalk ceased is likely to be marked by a diffuse boundary, as burrowing organisms are likely to have incorporated some white chalk into the marly chalk. Taking all the above into consideration, it is apparent that bioturbation results in the vertical expansion of a marl seam and considerable modification of its' form.

These theoretical arguments are in good agreement with field observations (see above and Appendix 2), suggesting that near-surface post-depositional bioturbation has had a marked effect on the final form of marl seams, effectively increasing their thickness and diluting the clay-rich chalk with carbonate. Applying the above arguments to Glynde Marl 1 [Caburn, New Pit, Beachy Head] (see description above), the implication is that the marly chalk was either introduced into sediments which only contained a small bottom dwelling fauna incapable of fully reworking the sediment, or the marly chalk was introduced so quickly that it prevented much of the 'usual'

reworking. Consequently, Glynde 1 [Caburn, New Pit, Beachy Head] may represent a marl seam virtually unaffected by bioturbation, preserved as it was deposited (although subsequently compacted). Furthermore, if Glynde 1 [Caburn, New Pit, Beachy Head] is more representative of a freshly deposited marl, the implication is that carbonate sedimentation was either much reduced, or that the clay-rich chalk was deposited very quickly. It is interesting to note that many of the marls within the Northern Province have a similar appearance and texture to Glynde 1 [Caburn, New Pit, Beachy Head].

c) Above the marl seam

Although the tops of marls are usually gradational, burrows can be observed passing upwards into the overlying white chalks. They usually lighten upwards and have usually been altered to flasers by post-burial pressure solution. They are discussed further in Section 2.9.

2.5.4 Summary of marl bands containing marl seams and a model for their formation

1. All the evidence indicates that they are of primary origin and were formed on the sea floor.

2. There is no sedimentary evidence of widespread, syndepositional carbonate dissolution.

3. They are found on a variety of chalk substrates, implying that a break or decrease in sedimentation is not required for their formation.

4. Bioturbation has modified the form of most marl bands in the Anglo-Paris Basin in the following ways:

   a. Burrows below the marl seam are infilled with marly chalk.

   b. Mixed layer bioturbation has effectively moved the base of the seam downwards by 2-3 cm. The actual commencement of marly chalk deposition is defined by a more clay-rich band slightly above the base.

c. Bioturbation during and after the deposition of the marly chalk has resulted in its 'dilution' with variable quantities of white chalk.

d. The end of marly chalk deposition is not clearly defined.

e. Deeper burrowing organisms have reworked parts of the marly chalk after its burial, and have subsequently either been infilled with white chalk or have resulted in the formation of upward trending flasers.

5. Glynde Marl 1 [Caburn, New Pit Depot and Beachy Head] appears to contain an example of a marl seam which has only been slightly affected by bioturbation.

A model for the formation of marl bands containing marl seam is presented in Figure 2.5. It is based on the assumption that they were formed by an influx of non-carbonate material, whilst carbonate deposition continued unaffected. Bioturbation is seen as having a marked effect on the final form of the marl band: pre-marl burrows are infilled by the marly chalk, the deposited non-carbonate material is diluted with carbonate by bioturbation, and subsequent to the formation of the marl burrowing organisms from above transport some of the marly chalk upwards.

2.6 FLASER MARLS

2.6.1 Introduction

Flaser marl bands (marl types C, D, E and F) are closely related to both marl bands containing marl seams, and flaser chalks. Mortimore and Pomerol (1987) showed that flaser marls at some localities (for example Malling Street 1 at Dover) can be correlated with marl seams at other localities (Malling Street 1 at Southerham Works Pit, Lewes), whilst in the cliffs at Dover (between Langdon Stairs and St Margarets Bay) Bridgewick Marl 2 changes briefly into a flaser marl (see Plate 3b). They differ from flaser chalks because of their lateral continuity and their higher clay content. In terms of form there is a complete gradation between a marl seam and a flaser marl, making any classification slightly subjective.

2.6.2 Field description

Flaser marls vary in form, but usually consist of a well defined unit containing a series of intertwined, sub-horizontal layers of marly chalk separated by white or nodular chalk (Plates 2 and 3a). The boundary between the marl-rich and marl-poor chalk is often slightly indistinct. Scattered flasers often extend upwards and downwards from the main unit, but they thin and lighten in colour. The marly chalk within flaser marls is usually a uniform medium or dark grey indicating that they are not simply a product of compaction (see Section 2.9 which discusses flaser chalks). Individual flasers vary in thickness, but are generally less than 3 cm thick.

A prominent omission or erosion surface above a flaser marl often affects the form of the flasers: it may terminate upwards trending flasers, and organisms burrowing down from it may rework the softer marly chalk. Both features imply that the surface postdates the formation of the flaser marl. Likewise if a surface occurs below a flaser marl, individual flasers may pass downwards along the omission suite of burrows. Where nodules separate the flasers (for example: Malling Street Marl, Dover; Plate 2b) they are usually associated with a nodular omission or erosion surface above the flaser marl, their presence often resulting in differential compaction of the sediments, deforming the flasers and resulting in some dissolution of the carbonate within the marly chalk (see Sections 2.9 and 6.3.2d).

Compaction and pressure solution has affected flaser marls in areas which have undergone tectonic deformation (for example: parts of Dorset, Seaford Head), as the flasers often appear thinner and darker, implying that some carbonate dissolution has occurred.

The degree and effect of bioturbation on flaser marls is an important factor to be considered when discussing the origin of these features (see below), but it is difficult to determine its extent. Many of the flasers appear similar in form to *Thalassinoides* burrows, although this may simply be fortuitous. Additionally, occasional sharply defined *Planolites* or *Thalassinoides* infilled with white chalk can be seen reworking the marly chalk (see Plate 3a). A more detailed discussion on the possible role of bioturbation can be found in the following Sections.

2.6.3 Origin of flaser marls

Because of the very varied form which flaser marls exhibit it is difficult to envisage a single process which is capable of forming all forms seen, I

therefore suggest that flaser marls may be formed by more than one process. Some possible mechanisms are discussed below.

1. A partially developed marl seam

As noted in the introduction, Bridgewick Marl 2 between Langdon Stairs and St Margarets Bay changes briefly from a type B marl band into a type D (see Plate 3b). As the chalk above and below the marl shows no lithological change, it seems likely that the change in form of the marl band was related to a local decrease in the amount of marly chalk incorporated within the sediment. Even if a thin seam was formed, subsequent compaction and the presence of nodules within the sediment may have deformed it beyond recognition. Flasers occur because enough marly chalk was deposited to infill the 'sub-marl' burrows, and to be subsequently reworked upwards.

2. Bioturbation of a marl seam

Mortimore (1979) suggested that a flaser texture could be formed by post-burial, vigorous bioturbation of a marl seam and subsequent infilling of the burrows with white chalk. He believed that this process (followed by compaction) could so disfigure a marl seam as to make it un-recognisable, resulting in an apparent flaser marl. Although burrows are most certainly found within marl seams and flaser marls, they are usually distinct and well defined, having a very different appearance to most of the white lenses seen separating flasers. Additionally, the thickness of many flaser marls (New Pit Marl 1 at Puys is 20 cm thick) and the size of many of the white chalk lenses make the process difficult to envisage. It must therefore be concluded that although post-burial bioturbation of a marl seam has affected the final form, field evidence suggests that it is of minor significance and is unlikely to produce a flaser marl.

3. Deposition and subsequent erosion of a marl seam

The formation of a marl seam and its subsequent erosion (through winnowing) may leave the flasers below the seam intact, producing by default a flaser marl. Although initially the distribution of clay within the flasers would be asymmetrical (most clay-rich at the top), subsequent reworking of the burrows by organisms mixing in white chalk may result

in a more symmetrical pattern, with the central zone of the band being the most clay-rich. But winnowing of this type is likely to result in the formation of a nodular erosion surface directly above the flaser marl. Careful examination of a number of cleanly exposed flaser marls has failed to reveal any such features, and it must be concluded that although there may be examples of this formational process within the Chalk, it is not the prevailing process responsible for the formation of most flaser marls.

4. Intermittent deposition of marly chalk

In the Section on bioturbation within marl seams (2.5.3b) it was suggested that bioturbation caused the intermixing of marly chalk and white chalk, effectively diluting the marly chalk with white chalk and increasing the thickness of the seam. If the same idea is applied to flaser marls, the implication is that the volume of clay-rich material deposited is significantly less than the volume of marly chalk now infilling the flasers. Furthermore, the presence of the white chalk lenses is difficult to explain as one might expect the sediment to be homogenised by the bioturbational processes. Consideration of these problems raises the possibility that clay-rich chalk deposition was not continuous, but alternated with longer periods of white chalk deposition. Subsequent bioturbation diluted the clay-rich chalk with white chalk and removed most of the primary fabric. At a slightly deeper depth within the sediment the marly chalk layers were at least partially reworked by *Thalassinoides* to produce the intertwined effect now seen. The intermittent deposition of clay rich chalk has also been used by Khosrovschahian (1972) to explain some unusual features seen in slumped chalks in Germany.

This mechanism (or one very similar) appears to be the most likely one for the formation of true flaser marls such as New Pit 1 at Puys and Dover. The slightly unusual features displayed by New Pit Marl 1 at Beachy Head (marl seam overlain by a more flaserish unit) can also be explained using this method if, above the seam, white chalk sedimentation was interrupted by the deposition of additional thin, clay-rich units which were subsequently reworked. Figure 2.6 illustrates the sequence of events required to form a flaser marl using this method.

2.6.4 Summary of flaser marls

1. Field evidence indicates that flaser marls are a primary feature of the sediment, and were formed at or near the sediment-water interface.

2. They are found in a variety of chalk substrates, implying that a break or decrease in carbonate sedimentation was not required for their formation.

3. Because of their variable form, several processes can be proposed which explain their origin, of these the most plausible are:

a) A marl seam which suffers a local decrease in the amount of non-carbonate material.

b) Intermittent deposition of clay-rich chalk which is subsequently modified by bioturbation.

2.7 OMISSION AND EROSION SURFACES IN CHALKS

2.7.1 Introduction

Omission and erosion surfaces occur rhythmically throughout through the Chalk at spacings of between 0.2 and 2 m. Their form is very variable, but differences can usually be related to the length of time that deposition was halted for. They are most easily seen in the Lower Chalk and can be correlated over 100 000 km^2 (Gale, 1990). Recently it has been suggested (Ditchfield and Marshall, 1989) that the rhythmicity in the Lower Chalk is related to primary temperature fluctuations of up to 4.5°C, possibly related to orbital fluctuations of the Earth (Gale, 1990). In the Middle and Upper Chalk, surfaces are only revealed after extended periods of air weathering, or through constant wave washing. Both these processes will highlight any slight variations in composition and cementation of chalk.

The following discussion is important when considering the sedimentology of marl seams and flaser marls, as they have many features in common.

2.7.2 Description

An omission surface is defined as a minor break in the sedimentary column which marks a temporary halt or sudden decrease in the rate of sediment

deposition, but involves little or no erosion (Bromley 1975). An omission surface may undergo scouring to produce an erosion surface. In the field, omission and erosion (o/e) surfaces are defined on two criteria: firstly, the chalk below the surface may be partially cemented; secondly, there is a sharp change in sediment colour from white below the surface to light/medium grey above (Plates 6 and 7a). The grey chalk above the surface lightens in colour upwards, usually becoming 'white' before the next surface in the sequence. The topography of omission surfaces is irregular, probably due to bioturbation; whilst erosion surfaces usually have a relatively planar topography due to current scouring.

The difference in sediment colour above and below o/e surfaces is due to an increase in the percentage of clay in the sediment above the surface. This is either due to a relative decrease in the amount of carbonate being deposited, or a relative increase in the amount of clay within the system. The gradational nature of the grey to white chalk transition above the o/e surface suggests that the clay:carbonate ratio gradually decreased over time, but the effects of bioturbation must also be taken into consideration (see below).

Close examination of erosion surfaces shows that coarse, intraclastic chalk often lines the bottom of omission suite burrows, and patches of it can also be found on top of the surface. This sediment represents the 'residue' material which was not winnowed or eroded away whilst the erosion surface was exposed. Examination of chalk above erosion surfaces shows that there is a gradual upwards decrease in the amount of coarse material. This feature, and the increase in clay above the surface have been interpreted by Robinson (1986b) as reflecting cyclical fluctuations in current speeds within the Chalk Sea, possibly related to the influence of the Earth's orbital cycles on tidal patterns (current speed gradually decreasing above the erosion surface). Robinson argued that both features are due to winnowing of the fine carbonate fraction of the sediment, leaving cohesively bonded clays and coarse carbonate grains behind. This process is difficult to envisage as, whilst winnowing may leave behind coarse carbonate grains, the small quantity of clay which is usually present in white chalks is unlikely to easily form a cohesive mass, and is far more likely to be winnowed away with the fine carbonate fraction.

2.7.3 Bioturbation

An omission surface need not necessarily represent the actual point at which the change in sedimentation took place. Applying Berger *et al's* (1979; see Section 2.3.3) observations to omission surfaces within the Chalk, it seems likely that the change in sediment composition does not define the 'palaeo'sediment-water interface at the time of the change, but rather the boundary between the mixed zone and the transition zone below. Field evidence to support these suggestions includes the very delicate structures which omission surfaces frequently display; if the latter were exposed on the sea-floor it is very unlikely that they would be preserved. In contrast, erosion surfaces do represent the 'palaeo'sediment-water interface, but at the point in time that sedimentation commenced again, rather than the point at which sedimentation stopped.

The above discussion is vitally important when considering the effect that postomission bioturbation had on the sediments deposited during and after the formation of the erosion surface. As already noted, the fining upwards chalk found above erosion surfaces is unlikely to be caused by gradual decreases in current speed. A more plausible reason for this feature is that reworking of the calcarenitic lag, whilst within the mixed zone, 'carried' many of the coarser particles upwards. This process continued as the mixed zone migrated upwards, the proportion of calcarenitic material in the sediment decreasing due to dilution effects, eventually reaching zero, and giving rise to the observed gradational trend. A similar argument can be applied to the grey to white chalk gradation seen above both omission and erosion surfaces. Often the chalk infilling the omission suite of burrows is more clay-rich than that seen above the surface (and also that seen in the postomission burrows). This suggests that the most clay-rich sediment was deposited during the formation of the o/e surface. The gradational nature of the grey to white chalk transition is probably the result of a combination of primary change in sediment composition, and gradual dilution of the of the reworked clay-rich chalk from the surface. If this interpretation is correct, the formation of an o/e surface is probably due to a decrease in carbonate deposition, with non-carbonate deposition continuing unaffected. The formation of an erosion surface also requires an increase in current speed for at least part of the time.

2.7.4 Cementation

The chalk below o/e surfaces may be partially cemented (see Plates 6b and 7a), and the degree of cementation can be used as an indication of the length of time that deposition was slowed or halted for (Kennedy and Garrison, 1975): the greater the cementation, the greater the period of non-deposition (see Diagenetic Considerations, Section 2.8). If an erosion surface is exposed for a long period of time a fully lithified hardground will be produced (Plate 7b). An 'omission surface' will be formed by default if the composition of the sediment being deposited were to become more clay-rich. But most cleanly exposed omission surfaces, examined as part of this study, show at least slight evidence of cementation below the surface, although in many cases this may just be represented by slightly firmer chalk with a more irregular topography.

This observation also substantiates the earlier suggestion that o/e surfaces are the result of a decrease in the carbonate sedimentation rate, whilst non-carbonate deposition continued unaffected. Fluctuations in the latter would not have a noticeable affect on the rate of deposition, in contrast, a decrease in the deposition rate of the former would result in extended exposure of already deposited material at the mixed layer-transition layer boundary, culminating in the formation of nodules within this sediment. The cause of the cementation is discussed in Section 2.8.2a.

2.7.5 Model of formation, classification and summary

Figure 2.7 displays a model for the formation of omission and erosion surfaces, based on the assumption that they are formed as a result of a decrease in the rate of carbonate sedimentation. The model also demonstrates the effect of extended exposure on an omission or erosion surface, and the result of bioturbation on the final form of the surface.

It is possible to classify o/e surfaces according to the degree of cementation of the underlying chalk (see Figure 2.8). This classification is based, in part, on Kennedy and Garrison's (1975) classification of early cementation within chalks, but treats the cementation of the chalk to be a secondary effect caused by the formation of the o/e surface. The observations made as part of this project, and discussed above, are also included.

An *omission surface* is produced by a pause in carbonate sedimentation. Cementation of the white chalk below the surface is either

very weak or non-existent, and can only be discerned on fresh or heavily weathered exposures. The topography of the omission surface is irregular as it represents the boundary between the mixed zone and the transition zone, rather than the original surface.

If the surface undergoes winnowing or erosion during the break in deposition, an *erosion surface* is formed. This usually has a planar surface, and is overlain by patches of calcarenitic chalk which also infill parts of the omission suite of burrows. In common with an omission surface, there is little evidence of cementation below the surface.

Continued non-deposition of carbonate results in partial cementation of the chalk below the surface, producing a *nodular omission surface*. As with an omission surface, it represents the boundary between the mixed layer and the transition zone. The boundary is usually more contorted than that of an omission surface for two reasons: firstly, the longer depositional 'break' allows greater reworking of the sediment in both the mixed layer and transition zone; and secondly, the formation of nodules in white chalk at the boundary causes bioturbating organisms to deviate from their planned routes.

If, shortly after the recommencement of deposition, a further break occurs, permitting the growth of nodules down to the previous nodular omission surface, a *multiple nodular omission surface* is formed. Evidence for these is often slightly subjective, but it is possible to recognise nodules which are light or medium grey in colour overlying slightly harder white nodules. A similar feature may form through prolonged exposure of one surface if the downward 'growth' of nodules is sufficient for them to pass below an ordinary omission surface.

If a nodular omission surface undergoes scouring or winnowing, a *nodular erosion surface* is formed. Calcarenitic chalk can be found in omission suite burrows and in patches on the surface. Reworked (possibly bored and mineralized) nodules rest on the surface, sometimes forming an intraformational conglomerate. A similar feature is produced if the highest surface of a multiple nodular omission surface becomes exposed.

Repeated exposures in quick succession produce a *multiple nodular erosion surface*.

A longer period of non-deposition of carbonate (with no erosion or exposure) allows the nodules within the sediment to coalesce, producing a *fully cemented omission surface* (incipient hardground).

Scouring or winnowing of fully cemented chalks, or further cementation of an incipient hardground, results in the formation of a *hardground* (fully cemented erosion surface). The hardground is bored and often mineralized, as are the omission suite of burrows in the chalkstone (*sensu* Bromley and Gale, 1982) below. Bromley (1975) has shown that the chalkstone below a hardground may be composed of up to 14 different sediment types, implying a very complex history of formation. The sculpture and form of the hardground is also important, as it may give additional information concerning the formational history.

2.8 DIAGENETIC CONSIDERATIONS

2.8.1 Introduction

Sedimentary features of marl bands and omission surfaces have been affected to some degree by diagenesis prior to being re-exposed, and it is important to consider its possible effects. Because of the very pure nature of chalks, dissolution, reprecipitation and cementation of calcite are the three most important factors to be considered, they are discussed below.

2.8.2 Early diagenesis

a) Cementation

i) Introduction

Early cementation is found at many levels within the Chalk, and results in the formation of hardgrounds and nodular units. It is mainly due to the infilling of voids by microspar, and in a hardground it may occupy 35-45% of the chalk (Bathurst, 1975). The presence of an omission or erosion surface directly above cemented units implies that cementation occurred close to the sediment-water interface. Two different sources for the cement have been proposed, and are discussed in detail below

ii) Field characteristics

Field characteristics of early cemented units suggest that deposition either slowed down or was halted whilst they were being formed (see Section 2.7), furthermore the greater the degree of cementation, the greater the apparent time gap (for example: condensation associated with the Chalk Rock). The degree of cementation within any unit tends to decrease downwards (for example: the Chalk Rock hardgrounds overly fully lithified chalkstones, which in turn overly nodular chalks which become less cemented with depth). In nodular units, cementation tends to occur in the chalk between the omission suite of burrows, even in chalkstones some omission suite burrows remain uncemented (Bromley, 1975). Well developed nodular units frequently show some iron mineralization, resulting in the characteristic yellow staining of the cemented chalk. On hardgrounds and within chalkstones mineralization is often more complex, glauconite and calcium phosphate are the minerals most commonly present, and occur both on the hardground surface and on burrow walls within chalkstone (Bromley 1978).

iii) Source of the cement

There are two possible sources for the cement: it may be derived from the dissolution of aragonite or calcite within the sediment, either at depth or close to the site of cementation, or it may originate from sea water.

Several problems exist with an intra-sediment source for the cement, be it either aragonitic or calcitic. Field evidence has shown that aragonitic fossils are only preserved, as moulds, in early cemented chalks. This suggests that cementation had occurred prior to the dissolution of the aragonite, discounting it as a possible source. In contrast, Jenkyns (1974) has argued that nodules within the Ammonitico Rosso were in part formed by rhythmical supersaturation of near-surface porewaters with calcium and carbonate ions, as a result of aragonite dissolution within the sediment. The stability of low-Mg calcite usually precludes its near-surface dissolution, however Jenkyns (1974) believed that solution transfer of calcium carbonate was also instrumental in the formation of nodules within the Ammonitico Rosso, and resulted in 'unmixing' of the sediment. These interpretations are discussed further in Sections 2.9.6 and 2.9.7

Dissolution of low-Mg calcium carbonate at depth through pressure solution, followed by upwards migration, is a possible method of cementation but for

two important drawbacks: between 10 000 and 100 000 pore volumes of solution are required to fully cement one pore; and even rapidly moving pore fluids only travel 300 cm/year (Bathurst, 1975). If the low permeability of chalk is taken into consideration, the magnitude of these figures make it exceedingly difficult to envisage pressure solution at depth to be an important factor in influencing early cementation.

A sea water origin for the cement has been proposed by several authors (Kennedy and Garrison, 1975; Jeans, 1980; Jarvis, 1980c; Clayton, 1984) and, taking into account the difficulties with the alternative (above), this appears to be the most likely source. The observation that cementation decreases downwards strongly suggests that cementation commenced at the top of the unit, close to the sediment-water interface. The avoidance by cemented chalk of burrow systems (although the burrows become contorted when the degree of cementation is high) suggests that reworking of the sediment by the burrowers may have prevented cementation and, in addition, the higher porosity of the burrow systems may have aided cementation by enabling the deeper percolation of carbonate-rich waters. Jarvis (1980c) noted that the original sediment forming the hardground and the chalkstone below is usually coarser than the white chalk above and below, which he attributed to winnowing. He argued that the coarsening both aided the cementation process and allowed easier fluid flow.

b) Mechanical compaction and dewatering

The initial porosity of white chalk was probably between 70 and 80% (see Section 2.2); studies of similar Recent sediments (Schlanger and Douglas, 1974) suggests that this was reduced to between 50 and 60% through gravitational compaction and dewatering in the first 200 m of burial. During the early stages dewatering was probably aided by deep burrowing organisms (for example *Bathichnus*), whose burrows probably acted as natural conduits for the expelled water. The excellent preservation of such burrows also suggests that the sediment was firm a short distance below the sediment-water interface (although organic linings may have aided burrow preservation), and that dewatering below a depth of 1 to 2 m was a result of particle rotation to minimize stress, rather than as a result of large scale fluid movements.

A factor which must also be taken into consideration is the early dissolution of aragonite and other metastable minerals. Because their removal from the sediment probably occurred at the same time as much of the dewatering, it is very difficult to separate the two processes, and hence evaluate the contribution that their removal made to the compaction of the sediment.

Variation in the composition of the sediment may have an important effect on the dewatering process. The retention of water between clay particles and in the interlayer position within clay particles markedly retards the dewatering of clay-rich sediments when compared to carbonate-rich sediments (Rieke and Chilingarian, 1974). The amount of pore water retained depends on the degree of orientation and the packing of the particles, whilst the the amount of electrostatically bonded water depends on the surface area of the clay and its cation exchange capacity. Of the three principal clay minerals found in chalks (smectite, illite and kaolinite) smectite has by far the largest capacity for water retention, because of its thin, platy shape and its high cation exchange capacity. A freshly deposited smectite-rich clay has a porosity of around 80% (Rieke and Chilingarian, 1974), and there is a continuous, rapid decrease in porosity to a depth of approximately 500 m. Clay-rich sediments at or slightly beneath the sediment-water interface act as thick suspension, with the flow properties of liquids (Rieke and Chilingarian, 1974, p153). During compaction they are firstly transformed into one capable of flowing in a paste-like manner, before finally becoming non-Newtonian. The addition of quantities of calcium carbonate has a direct effect on the speed of dewatering: the more calcium carbonate added, the faster the dewatering takes place (Rieke and Chilingarian, 1974, p51)

Because calcite crystals do not have similar properties to clays, sediments containing a high percentage of calcite will dewater more quickly than those containing a high percentage of clay, especially in the very early stages of compaction. Additionally, the silty nature of much of the carbonate fraction in chalks probably resulted in the early construction of a lattice framework which, although retaining a high porosity, resulted in a rigid sediment more resistant to compaction. Corroborative evidence for this includes the presence of deep-burrowing trace fossils (*Thalassinoides* and *Bathichnus*) the burrows of which apparently needed no supportive linings.

Considering all the above evidence, it must be concluded that white chalks and marly chalks probably behaved in a very different way during the very early stages of compaction, and it appears likely that clay-rich sediments dewatered more slowly and behaved in a more plastic manner than clay-poor sediments (see also Bennett *et al.* 1989). Where a sediment consists of alternating clay-rich and carbonate-rich units (as is the case when marl seams are present), unusual and irregular features may result, especially at the boundary. Nodules within the sediment may also affect the final product, as their presence may result in differential compaction of the sediment above and below them.

c) Flints

i) Field relationships

Flints tend to occur in three main forms: 1. as beds of flint nodules; 2. as bedding parallel tabular flints; 3. as tabular flints concordant with fractures.

Although the lowest stratigraphic appearance of flints within the Chalk is variable from locality to locality, lithostratigraphic studies have shown that some flint bands have diagnostic features, such as shape or colour, which enable their recognition over extensive parts of the Anglo-Paris Basin (Mortimore, 1983, 1986a and b; Robinson, 1986a; Mortimore and Pomerol, 1987). In addition to the characterization of individual bands, it is also possible to recognise a flint maximum in the Upper Turonian (Mortimore and Wood, 1986), and an apparent lateral equivalent in the Chalk of the Northern Province. No explanation of this phenomena has as yet been produced.

Detailed sedimentary logging of wave-washed sections has shown that flints are preferentially found replacing or overgrowing burrow fills (Bromley and Ekdale, 1984b). The burrow most frequently replaced is *Thalassinoides* (Plate 8a), whilst others, for example *Zoophycos*, are occasionally preserved. The trace fossil *Bathichnus paramoudrae* is typically unsilicified, but often has a thick, vertical, ring-like flint (a paramoudra) encircling it. Burrow preservation in flint is variable, frequently the flint 'outgrows' the burrow, masking the original burrow shape.

Wave-washed sections also show that, in successions of white chalk, flint bands are often associated with omission surfaces, the concentration of flint nodules being greatest in burrows at, or slightly below, the level of the omission surface. In successions containing nodular chalks, flints are always developed in the softer burrowed chalk between the nodules (Plate 8b), occasionally almost encircling individual nodules. In the Haute Normandie region, flint bands are seen to follow the pattern of sedimentation along the banks of the channels (Quine, 1988), and in many cases are the best lithological feature for defining the pattern of sedimentation. Occasionally, fragmented flints are found within penecontemporaneous slumps and slides (Mortimore, 1986a p117), suggesting that flint formation occurred soon after burial. During the course of this study not one flint was found within a marl seam or any unit of marly chalk.

ii) The origin of flints

The most widely accepted model of flint genesis is that proposed by Clayton (1984, 1986), a summary of which is illustrated in Figure 2.9. Using this model, the observed field relationships of flints can be easily explained. The 'common' bedded, nodular flints result from widespread sulphate reduction at the oxic-anoxic boundary (possibly during a slight break in deposition when the boundary remained stable). The higher porosity of burrows allowed easier mixing at the boundary, and hence preferentially became the sites of silica precipitation. Bedded, tabular flints were produced in sediments which had less marked porosity contrasts, and early compaction joints (with high porosity) became the sites of tabular flints discordant to bedding. Paramoudras were produced by localised anoxic conditions due to the high organic content of the trace fossil burrow *Bathichnus*.

2.8.3 Later diagenesis: pressure solution

Subsequent to any early cementation and dewatering, the most important diagenetic process affecting chalks is cementation caused by pressure solution and local reprecipitation of calcite. As a generalization, it results in a decrease in porosity and permeability directly related to burial depth. Calculations by Neugebauer (1974) have shown that the pressure solution of

low-Mg calcite and its reprecipitation as a cement is insignificant at depths of up to 300 m, and a volume of cement greater than 0.5- 5% is not generated before an overload corresponding to a depth of 1000 m is attained. Furthermore, Neugebauer argued that the stable form of coccolith plates made them difficult to dissolve and impeded cementation, relative to other carbonate fossils (for example forams and *inoceramids*). The presence of clays within a sediment has been found to aid pressure solution by providing a pathway along which the diffusion of carbonate ions can take place (Weyl, 1959; De Boer, 1977; Schlanger, 1964; Oldershaw and Scoffin, 1967; Mossop, 1972). Reprecipitation of carbonate ions usually occurs in nearby sites centimetres to metres away.

As chalks in the Anglo-Paris Basin have all been buried to approximately equivalent depths prior to their re-exposure (Scholle, 1977), they should all display similar later diagenetic features. This is true in most areas (including Kent, Sussex and the French coast), but there are a few exceptions, notably parts of Dorset and the Isle of Wight. In both these areas the Chalk underwent relatively severe tectonic deformation caused by the formation in the Miocene of the synonymous Purbeck and Isle of Wight monoclines (Osborne White, 1921; Arkell, 1938). The tectonic stresses applied to the Chalk caused additional pressure solution and reprecipitation (Mimran, 1977), possibly aided by the presence of meteoric derived pore-fluids (see below), and resulting in a more compact and harder sequence (a porosity of 26% as opposed to one of 43% for Kent; Scholle, 1977).

2.9 FLASERS AND FLASER CHALKS

2.9.1 Introduction

Flasers and Flaser chalks are general features of the Chalk which may also be associated with marl bands. The aim of this Section is to discuss their distribution, form and origin.

2.9.2 General description

Flasers are sinuous, clay-rich wisps varying in colour from light to dark grey. Their occurrence is usually associated with an omission or erosion surface, or with a marl band. They may occur above, below or at the same

level as a surface (Plates 10 and 11), but, are only seen above and below marl seams and flaser marls. Although isolated flasers are found, most examples consist of branching and combining groups and the whole unit is then described as a flaser chalk. Their thickness is very variable: individual ones are usually between 1 mm and 2 cm thick, whilst a thickness of up to 5 cm is possible for a group. It must be emphasized that, although for descriptive purposes flasers associated with omission and erosion surfaces are described as occurring at three lithological heights, they are not isolated from each other and, for example, flasers found above a surface may link with those below the surface.

2.9.3 Field terminology

The term 'flaser chalk' is derived from the German 'flaserkalk' (lens limestone) and was applied to the Chalk by Garrison and Kennedy (1977). Mortimore (1979, 1986a) has argued against the use of this term because of prior. igneous, metamorphic and sedimentary applications; he proposed that 'griotte texture' (see Tucker, 1974) should be used as an alternative. However, because 'griotte' is already used as both a lithofacies and lithostratigraphic term, it would be unwise to describe each clay parting as 'a griotte'. Mortimore avoided this problem by by calling all clay partings 'marl seams' or stylolites; I believe that the use of the term 'marl seam' in this context is incorrect (see definitions in Chapter 1). To avoid confusion and the creation of additional names, I shall adopt Garrison and Kennedy's nomenclature, using the term 'flaser chalk' to define the texture, and 'flaser' to describe an individual clay parting (see Chapter 1); it must be stressed that, within this work, these terms are used exclusively for features found within chalk, and do not relate to similarly named textures found in other rock types.

Detailed field examinations have shown that it is possible to subdivide flaser chalks into three main categories (see also Garrison and Kennedy, 1977):

If the flasers enclose white chalk, a *flaser chalk* is formed.

If the flasers enclose nodular chalk, a *nodular flaser chalk* is formed.

If the flasers enclose chalk intraclasts, an *intraclastic flaser chalk* is formed.

2.9.4 Stratigraphic distribution

Flaser chalks do not occur throughout the Middle and Upper Chalk of the Anglo-Paris Basin, they are probably most abundant in the Turonian, and it is at this level that much of the following investigation has been undertaken.

Even in the Turonian there is a great deal of stratigraphic variation. In the Lower Turonian, nodular flaser chalks are common in both the heavily condensed succession seen at Dover, and also in the relatively expanded successions seen at Eastbourne and Puys. In the Middle Turonian, flaser chalks and nodular flaser chalks are locally developed above the Glynde Marls in Sussex, but usually only occur again in significant numbers below the Southerham Marls, continuing to be found within parts of the sediment until the level of the Bridgewick Marls. In the Upper Turonian (above the Bridgewick Marls) there are very few flaser chalks, a situation which continues for most of the Coniacian and Santonian. In the Upper Santonian and Lower Campanian, flaser chalks are again found, but in smaller numbers than in the Turonian.

2.9.5 Field descriptions

a) Flasers associated with omission and erosion surfaces

i) Flasers found above surfaces

Flasers may occur in the light grey chalk above omission and erosion surfaces, although commonly only in sequences containing strong nodular chalks and/or hardgrounds. At localities where they are found above weak omission surfaces, the sediment tends to have suffered some additional tectonic deformation (for example: Seaford Head), and the flasers produced tend to be poorly developed and irregular.

They occupy a variable thickness of the sediment but, if present in large numbers between nodular units, they may extend to the base of the nodular unit above. Flasers of this type are usually sub-horizontal and slightly undulating, although in areas of more steeply dipping strata they may be inclined to the original bedding.

ii) Flasers found at surfaces

Flasers can often be seen 'draping' over omission and erosion surfaces. They are most commonly found on nodular omission surfaces and incipient hardgrounds, but weaker examples can be found on poorly cemented surfaces. The flaser drape is preferentially found above nodules; in the chalk between the nodules (where omission and postomission burrows pass through the surface) the flasers quickly expand, weaken, and finally disappear. If intraclasts are present on the surface, they often have flasers passing over and between them.

iii) Flasers found below surfaces

This is the position where flasers are most commonly found. They occur below omission and erosion surfaces, and below nodular surfaces and incipient hardgrounds. Occurrences tend to decrease if the nodules have coalesced to form a rigid framework, and no examples of flasers have been found within chalkstones.

The form of the flasers is very variable. Below simple omission and erosion surfaces flasers appear to remain within the omission and postomission suites of burrows, and are usually medium grey, sub-horizontal, smoothly undulating and with gradational edges. In contrast, flasers found below nodular surfaces are often thin, very irregular, with sharp edges and usually dark grey in colour. Flasers always pass between and around nodules, rather than through them; this may give the chalk a 'chickenwire' pattern (see Garrison and Kennedy, 1977, fig 11). Flasers passing between nodules may become stylolitic and, if movement occurs, clay-rich slickensides are formed. Flasers also expand and weaken when entering the softer, light grey 'burrow' chalk found between nodules; this may produce a 'horsetail' effect, with one flaser splitting into many, usually thinner, ones (Plates 12 and 13). If flints are developed below a surface, flasers are often seen to expand and weaken close to them (Plate 12b).

b) Flasers associated with marl bands

Flasers associated with marl bands have similar characteristics to those found above and below omission and erosion surfaces, and are influenced by early cemented chalks in much the same manner. They are more

frequently found above marl seams than below them, particularly if the upper part of the seam is gradational. Flaser marls usually have thinner, irregular flasers extending upwards and downwards from them.

2.9.6 Review of previous work

Much work has been carried out concerning origin of flaser chalks. Similar features are seen in rocks of other ages, for example: the Ammonitico Rosso (Hollmann, 1962, 1964; Jenkyns, 1974) and the Griotte of the Montagne Noire (Tucker, 1974). This Section will first discuss previous work on flasers in the Chalk, and then discuss similar features seen elsewhere.

Flaser chalks have been described by several authors (Peak and Hancock, 1961; Voigt, 1962; Voigt and Häntzschel, 1964; Kennedy, 1969 and Kennedy and Garrison, 1975), and Hancock (1975a) undertook the first detailed discussion of their origin. He argued that preferential solution had caused the flasering, suggesting that it occurred after the infilling of burrows but before the production of penecontemporaneous compaction faults. Two of Hancock's examples can however be reinterpreted: plate 2d is probably a series of zoophycos burrows offset by faulting, whilst plate 2c shows reworking of a large burrow and subsequent infilling with lighter sediment.

In contrast to Hancock's interpretation, Garrison and Kennedy (1977) argued that flaser chalk was a product of late diagenetic solution and compaction, and suggested that it was a soft sediment analogue of stylolites (an argument repeated by Scholle, 1977). However, many of their examples were taken from either Ballard Head in Dorset or the Isle of Wight, which, as already noted (see Section 2.8.3), are atypical sections due to additional tectonic deformation. Furthermore, many of their small-scale examples were taken from within marl seams and flaser marls, these features, although similar, may have been caused by other processes (see Section 2.10).

Mortimore (1979) discussed the origin of the flaser texture, but he concentrated on flaser marls, and avoided discussing the more general case (see Section 2.7.5).

Eller (1981, 1984) described similar features from within the Red Chalk of eastern England. However, in contrast to my observations from chalks of

the Anglo-Paris Basin, he believed that the clay-rich flasers represented burrow systems, whilst the light grey chalk through which they often passed was produced by dissolution. He envisaged the outwards percolation of acids from the burrow derived from aerobic respiration, and sulphide oxidation of the burrow walls, as being the primary causes of the dissolution. The major difficulty with applying this interpretation to chalks of the Anglo-Paris Basin is that the 'diagenetically' produced light grey chalk is often found without a dark grey 'burrow' in its centre. Indeed, the usual interpretation applied to these light grey chalks (see Section 2.3; Bromley, 1967(a), 1975) is that they infill the omission suite of burrows. Much of this confusion probably resulted from Eller's belief that many of the burrows had a more clay-rich wall, a feature not previously described from the Chalk (see Bromley, 1967(a)). It can be reinterpreted as reworking of clay-rich omission suite burrows by postomission burrows, which were subsequently infilled with a lighter sediment. His petrographic evidence, which shows that much of the light grey chalk contains microstylolites (see Wanless, 1979), can also be re-interpreted, and probably shows grain reorganisation associated with sediment consolidation.

Wanless (1979), although discussing the more general topic of limestone response to stress, believed that the formation of nodules, 'deformation' of the matrix and pressure solution are concurrent aspects of the same process. However, he did not suggest at what depth this process took place and, furthermore, he believed that the formation of nodules is due to pressure solution although there is abundant evident to the contrary (see Section 2.8.2)

Hollmann (1962, 1964) discussed the origin of the texture seen in the Ammonitico Rosso, a Jurassic sediment which is comprised of carbonate nodules set in a marly matrix (similar in style to nodular and intraclastic flaser chalks). He proposed that it was formed by cyclical, irregular, limestone corrosion on the sea floor, resulting in a sediment consisting of limestone remnants set in an insoluble marly matrix. Jenkyns (1974) disagreed with this model, suggesting instead that the nodules resulted from precipitation of high-Mg calcite due to rhythmical supersaturation of the porewaters with calcium and carbonate ions (due to aragonite dissolution), and solution transfer of fine grained calcium carbonate. This process resulted in 'unmixing' of the sediment, which was subsequently deformed by compaction and pressure solution. Both these models assume constant (slow) sedimentation rates and some form of early dissolution to

produce the nodules. If however deposition was not constant, a model for nodule formation similar to that for the Chalk (see Section 2.8.2) can be applied, and likewise, the marly matrix may also have been formed by a related process.

Tucker (1974) discussed the sedimentology of Devonian Griotte (southern France) and Cephalopodenkalk (Germany). He envisaged a similar process to that of Jenkyns (1974) for the formation of the 'griotte texture'.

2.9.7 Discussion on the development of flaser chalks associated with omission and erosion surfaces

Although some of the above works noted that flasers are preferentially found in relatively clay-rich sediments, none of them discussed the primary control that lithological variation has on the production and growth of flasers. Later compaction and pressure solution may have played a part in producing the features seen today, but selective pressure solution implies prior inhomogeneity within the sediment (Park and Schot, 1968). Field evidence implies that the distribution of omission and erosion surfaces, and their associated omission and postomission burrows, are the most important controls on the subsequent distribution of flasers in chalks (Figure 2.10).

The infilling of omission and postomission burrow systems by more clay-rich chalk was the prime factor in the subsequent production of flasers below a surface. Not only was the infilling sediment compositionally inhomogeneous with the sediment surrounding the borrow, but it was also relatively uncompacted. Furthermore, during compaction, the clay-rich nature of the burrow fill aided pressure solution by increasing the number of diffusional pathways available to the dissolved ions.

The presence of early diagenetic nodules within the sediment created further inhomogeneity. During compaction, stress was concentrated at the nodule-soft chalk boundaries, causing additional plastic deformation of the incompetent softer chalk. This had the effect of further distorting the already deformed burrow systems, subsequently producing very 'deformed' flasers. Stylolitic flasers, found between vertically adjacent nodules, were probably produce as a result of intensive compaction and squeezing of a burrow. As noted by Purser (1969), the production of a framework through coalescence of nodules decreased the amount of flasering because the whole

unit behaved in a rigid manner, preventing compaction of the inter-nodular softer chalks. Likewise, flasers are not seen in chalkstones because the sediment was fully cemented prior to compaction.

The weakening of flasers close to flints is due to the preferential growth of flints within burrow systems (see Section 2.8.2c). Because flints are believed to have formed and become rigid at relatively shallow depths, subsequent compaction of the sediment has not markedly affect them, and their presence may have produced a 'shadow' of less compacted chalk at right angles to the stress direction. Therefore, although compactional effects may have produced burrow flasers in much of the sediment, as the burrows entered the flint's 'compactional shadow' they became progressively less deformed, and may retain their original form adjecent to the flint.

The presence of flasers at the omission or erosion surface is due to similar factors to those controlling the development of flasers below the surface, but the piping down of more clay-rich chalks to produce an inhomogeneous sediment is not required. Slight cementation of the surface aided the development of flasers, their degree of deformation being partly controlled by it. Flasers are not usually seen in the omission and postomission suite burrows which 'pass through' the surface, as (assuming that the stresses were related to burial depth) the sediment was relatively homogeneous in the direction of maximum compaction. The application of a secondary stress from another direction (possibly due to subsequent deformation), may have allowed the production of flasers which 'pass through' the surface. Flaser development between intraclasts is due to a similar processes to that forming them between nodules. Surprisingly, flasers are not always seen on hardgrounds, as might be expected from the above discussion. A possible reason for this is that the uniform nature of the cemented surface may have caused the compactional stresses to be evenly spread over the succeeding units, effectively dissipating it.

The occasional occurrence of flasers above a surface is usually related to the presence of strong nodular units or hardgrounds, or post-depositional tectonic activity. Again, their development was due to inhomogeneities within the sediment, but this time on a larger scale. As noted above, the development of a nodular framework or chalkstone prevented further compaction of that sedimentary unit; assuming that the stress applied to the well cemented unit could not be 'lost' from the system, it must have been absorbed by adjacent, weaker units. In a sequence containing well cemented surfaces, the weakest units are the softer, clay rich units found

above the surfaces, and consequently these absorbed the compactional stress 'passed on' by the cemented units. If the stress was great enough, flasers were produced. Because today, the softer units appear relatively homogeneous, it is impossible to say if the position of flasers is related to weak, primary inhomogeneities such as burrows. Post-depositional tectonic activity may have produced a similar effect above only weakly cemented surfaces (for example, at Seaford Head), even if the sediments were already relatively well compacted.

2.9.8 Discussion on the development of flasers associated with marl bands.

As with flasers associated with omission and erosion surfaces, those associated with marl bands are likely to have been formed as a result of pressure solution on an inhomogeneous sediment. In this case the reason for the inhomogeneity is the action of bioturbating organisms which, during their reworking of the sediment, incorporated some of the marly chalk from the seam or flaser marl into their burrow. Flasers below marls tend to be the same colour as the marl when close to the seam, but lighten away from the seam, possibly reflecting the effect of intra-burrow reworking on the marly chalk. In this respect, the clay-rich nature of flasers beneath marls differs from those beneath omission and erosion surfaces: the latter are primarily a product of diagenetic compaction and dissolution, whilst the fill of the former is part-primary.

Flasers found above marls usually lighten in colour upwards, implying that the source of the marly chalk was the marl seam or flaser marl. Their method of formation differs slightly from those found below marls as the bioturbating organism carried the marly chalk upwards after reworking the seam. This process may have been aided by the slightly more fluid nature of the marly chalk in the seam during early dewatering, as burrows entering the marl from above would have acted as conduits for water to escape, which in turn may have assisted in the transportation of clays.

On a larger scale, marl seams and flaser marls can be described as inhomogeneities within the sediment, and can therefore be expected to show both the effects of dissolution during burial, and also absorb the stress which would otherwise have been directed at the firmer units above and below. There is good evidence to suggest that marls have indeed suffered from the effects of compaction during diagenesis (see Geochemistry and Petrography), but the amount of stress that they can

absorb is finite and they will eventually become as rigid as the chalks above and below. When this point is reached, flasers will start to develop above and below the marl.

2.9.9 Summary of the position and form of flasers.

The position and form of flasers is controlled by a combination of the amount of compaction and the degree of cementation of the chalk above and below. If the amount compaction is low, and the chalk above and below is un- or very weakly cemented, flasers tend to be very diffuse, consisting of numerous thin, wispy streaks of clay-rich chalk. If the degree of cementation of the chalk above and below is uneven, the stress pattern results in well defined flasers developed adjacent to the better cemented chalk (at the top or the bottom). If the chalk above and below is well cemented, and compaction is still relatively low, flasers are developed adjacent to both edges of the burrow, the centre of the burrow being only slightly affected.

With an increase in the amount of compaction, flasers in weakly cemented chalks become much more well defined, and also much thinner. If cementation of the chalk is uneven, pronounced flasers are produced adjacent to the better cemented chalk and, in extreme cases, the flaser 'drapes' around the nodule due to plastic flow of the softer chalk. If the chalk above and below is equally well cemented, flasers become well defined and often irregular. In extreme cases (or where the initial burrow was very narrow) a stylolitic flaser is produced. At this level of compaction, there is often little evidence to suggest that the burrow pattern below a surface controlled the development of flasers, dissolution having 'removed' most of the original burrow chalk.

Flasers associated with marls are influenced by the same factors as those controlling their formation at omission surfaces. However, before flaser formation can proceed, the marl itself is likely to undergo some carbonate dissolution and compaction in order to reach the same degree of firmness as the white chalk above and below.

2.9.10 Depth of dissolution.

The above discussions strongly suggest that flaser chalks are a diagenetic product caused by compaction, although their pattern is governed by

original sedimentary features. Kennedy and Garrison (1977) also believed that flaser chalks are a product of diagenesis. They suggested that, as pressure solution is insignificant above 300 m (Neugebauer, 1974), and at depths below 1000-2000 m substantial chalk lithification has already occurred, flasers must, by default, be formed between 300 and 2000 m. This argument has many flaws: firstly, Neugebauer's calculations did not take into account the presence of clays, which greatly aids the process of pressure solution (see Section 2.8.3), as does the presence of early diagenetic nodules (Bathurst, 1984). In addition, as Hancock (1975a) noted, flasers are often displaced by penecontemporaneous, small-scale faults, probably produced during dewatering. Hancock believed that flaser chalk formation was also penecontemporaneous, but the effect that flints have on flasers (see above) shows that they were formed after flint production (believed to have occurred at 5-10 m within the sediment; Clayton, 1986), and so they probably did not develop until buried to a reasonable depth. The depth of 2000 m must therefore be considered an absolute maximum, and it appears likely that the development of flasers was already much advanced at depths shallower than 300 m.

2.9.11 Factors affecting the distribution of flaser chalks

As noted above, flaser chalks are not developed to the same degree throughout the Middle and Upper Chalk. Whilst the lithology of the surrounding chalk is probably an important factor in their development, the presence of, for example, nodular chalks is not a guarantee that numerous flasers will also be developed; this is the case found in the relatively condensed succession between the Bridgewick Marls and the Dover Top Rock at Dover, and also at the same stratigraphic level in the more expanded successions in Sussex. This suggests that the amount of clay present within the 'clay-rich' sediment is also of importance and, assuming that the compactional forces applied during burial at each locality were relatively constant for Turonian sediments, it appears that the percentage of clay must reach a threshold value prior to the development of flasers.

2.10 DIAGENETIC FEATURES WITHIN MARL SEAMS

Although previous authors (Garrison and Kennedy, 1977; Ernst, 1982) have argued that marls are at least in part a diagenetic feature, there is no

evidence for widespread dissolution of the carbonate fraction of the marly chalk (see Geochemistry and Mineralogy). Indeed, many of the features previously believed to be caused by dissolution can be attributed to the effects of de-watering. An important consideration is the possibility that retention of water within the clays of the marly chalk may have retarded the de-watering of the marl seam (see Section 2.8.2b), in comparison to the white chalk above and below. Consequently the marly chalk may have behaved in a more fluid manner than the white chalk.

Where reworking burrows infilled with white chalk are found within marl seams, they often (especially those emplaced at a very early stage) contain thin, sub-horizontal 'stylolitic' wisps of marly chalk which Garrison and Kennedy (1977) proposed as evidence of dissolution through pressure solution. As the marly chalk which encloses the burrows is of primary origin, and the wisps merge into it at the edge of the burrow, it seems more likely that they are also of primary origin, possibly related to slight lateral movements of the marly chalk during early compaction. Movements of this type would result in plastic deformation of the marly chalk, but brittle deformation of the more rigid white chalk, producing weaknesses or small-scale fractures subsequently exploited and infilled by marly chalk. An alternative possibility for some of the features is that subsequent reworking of the burrow by a different sized organism resulted in the redistribution of some of the marly chalk, to the extent that it lined the new burrow.

Similarly, Garrison and Kennedy (1977) figured examples of chalk 'lenses' with sub-horizontal, diffuse 'tails' on either side, which they again argued were produced through dissolution. But within marl seams it is only white chalk-filled burrows which show this feature; white chalk intraclasts display sharp well defined outlines with no evidence of 'tails'. Assuming that the white chalk intraclasts were harder than burrow infills, it is more likely that this feature is derived from a combination of fluid flow and compaction. The effect of these two processes may have caused short distance transportation of some of the softer burrow infill, from the areas of relatively higher stress at the top and bottom of the burrow to areas of lower stress at the sides. The firmer intraclastic chalk may have resisted this, and was consequently affected by pressure solution, evidence for which can be seen in the slightly harder marly chalk which often surrounds them (e.g. Plate 9).

Post-burial tectonic activity has often exploited marl seams, treating them as slip-planes, because the are composed of structurally weaker material than the white chalk above and below. Thus in the section at Seaford Head, marls are often thinned and deformed, frequently containing a white chalk breccia derived from movement of the chalk above or below the seam.

3. MINERALOGY

3.1 SUMMARY OF MINERALOGY

Because the carbonate fraction of chalks has a near-constant mineralogy, work has concentrated on the non-carbonate fraction.

3.1.1 Fine silt and clay fraction

The mineralogical composition of marl seams is similar to that of white chalks above and below, although it may change slightly between localities.

In much of the Middle and Upper Turonian, variation in the relative proportions of smectite and illite within marls appear to reflect changes in sea-level. Samples from the lower Middle and Lower Turonian do not follow this pattern, possibly because of higher current activity.

Throughout the whole of the Turonian the relative proportions of smectite and illite in white chalks remains near constant. It is similar to that of marls in the lower Middle Turonian, but is markedly different to marls from the upper Middle and Upper Turonian. This may reflect:

a) Basin-wide homogenisation of the clay mineralogy of white chalks through bioturbation and winnowing.

b) The presence of aeolian transported illite.

3.1.2 Coarse fraction

The coarse fraction of marls and white chalks is composed of a mixture of quartz, calcium phosphate, pyrite, glauconite, limonite and occasional organic spherules. There is no evidence of volcanic material.

Detrital quartz grains may have undergone aeolian or water transportation prior to deposition. Grains of calcium phosphate are probably derived from fish and other vertebrates. Pyrite and glauconite are both authigenic, and were produced during early diagenesis; some grains have subsequently been weathered, forming limonite. Organic spherules were noted and are likely to be of algal origin.

3.2 GENERAL INTRODUCTION AND PREVIOUS WORK

3.2.1 Carbonate mineralogy

Upper Cretaceous White Chalk may contain up to 99% low-magnesium calcite, a composition which it has retained since deposition (Hancock, 1975a). The inherent stability of low-Mg calcite has retarded or prevented many of the diagenetic processes which affect 'ordinary' limestones (see Bathurst, 1975); as a consequence chalks are usually only slightly modified by post-depositional processes.

It is possible to separate calcite particles into two main groups based on particle size: 0.5-4 μm and 10-100 μm (Hancock, 1975a; Black, 1980), they make up 90% of the carbonate fraction. The proportions of the two groups varies from locality to locality but the finer fraction usually makes up 75-90% of the rock (Black, 1953; Håkansson *et al.*, 1974). Most of the coarser fraction is composed of Foraminifera, calcispheres, and fragments of bivalves, bryozoa and echinoderm plates. The finer fraction is composed of coccoliths (rings of plates formed by planktic marine algae of the class Haptophyceae) and their disintegrated plates.

In addition to the above components, chalk is also believed to have contained an aragonitic fauna. Evidence for this includes: moulds preserved in chalkstones of the Chalk Rock Member (Bromley, 1965), rare moulds preserved in cemented chalk nodules (Kennedy and Garrison, 1975), and very rare examples in white chalks where the shell has been replaced by minerals such as phosphate (Hancock, 1975a). The absence of an aragonite fauna over much of the Anglo-Paris Basin is frequently attributed to factors such as an unsuitable environment for the organisms (Kauffman *in* Hancock, 1975a). Hudson (1967) argued that their preservation within the Chalk Rock Member is due to palaeoceanic conditions, which allowed the aragonite compensation depth to rise above the depth of 'normal' chalk deposition, but below the depth at which the Chalk Rock was being formed. It seems far more likely that an aragonitic fauna was in fact widespread, as indicated by the presence of gastropod impressions on oyster attachment areas (Jefferies, 1961; Hudson, 1967). Non-preservation of the fauna over much of the Basin is probably due to early dissolution of aragonite either within the sediment or on the sea-floor, any moulds being obliterated by subsequent compaction (Kennedy and Garrison, 1975 p334, observed examples of compacted composite moulds derived from the aragonitic fauna).

Preservation of moulds in chalkstones is probably a reflection of the very early nature of the cement, which entered the sediment prior to dissolution of the aragonite, and prevented subsequent compaction of the mould.

3.2.2 Non-carbonate mineralogy

All chalk contains a small amount of non-carbonate material. In white chalk this accounts for between 1 and 5 percent of the total sediment; whilst in marly chalk it can account for up to 65 percent of the total (Pacey, 1984). Unfortunately, most earlier work on this fraction included no details of the precise sediment type (marl, white chalk, nodular chalk etc.).

It is possible to divide the non-carbonate fraction into three: minerals of biogenic origin, of detrital origin, and of authigenic origin. Silica and carbonate-apatite are the prime biogenic minerals found in chalks. The former originated from siliceous sponges (now preserved in calcite and limonite), but diagenetic processes caused its redistribution, producing flints. Much of the carbonate-apatite shows good evidence of being derived from fish (A.S. Gale *pers. comm.*; Deer *et al.*, 1966, p509).

Detrital minerals in the sand to fine silt fractions include: quartz (angular to rounded), and heavy minerals such as zircon, magnetite and tourmaline (Weir and Catt, 1965).

Authigenic minerals in the sand to fine silt fractions include: alkali feldspar, euhedral quartz, flint (both interlocking quartz crystals and opaline silica), glauconite, limonite and pyrite (Weir and Catt, 1965). Weir and Catt also argued that much of the apatite is also of authigenic origin due to the euhedral shape of many crystals.

In the clay fraction (<2 μm) the dominant minerals are smectite, mica (illite), quartz and apatite (Hancock, 1975a). Jeans (1968) proposed that in some cases smectite in the Lower Chalk is detrital, although it is more commonly neoformed. Weir and Catt (1965) also believed that smectite found in white chalk samples from Sussex is authigenic due to its' well-crystallized nature. Illite in the Lower Chalk may either be of detrital or authigenic origin (Jeans, 1968). Most workers who have examined insoluble residues from the Middle and Upper Chalk (Weir and Catt, 1965; Spears, 1979; Pacey, 1984; Robinson, 1984) have proposed that the illite is of detrital origin. Kaolinite is occasionally found (Mortimore, 1979) but is more common in the Lower Chalk (Jeans, 1968; Pitman, 1978), and is believed to be of detrital origin. Clinoptinolite (a zeolite) has been reported

by Robinson (1984) and Pomerol and Aubry (1977), the latter argued that it represents in situ alteration of volcanic ashfalls (see also Deer *et al.* 1963 p384). Chamley (1989, p264) disputes this, and argues that clinoptinolite may develop from the evolution of biogenic opal CT during diagenesis. Rare-earth element studies of clinoptinolite-free marls presented in this work appear to show that, in both white and marly chalks, clay minerals are of detrital origin (see Sections 6.3.2 and 6.3.3).

3.3 INTRODUCTION TO PRESENT STUDIES

3.3.1 Introduction

The homogeneous mineralogy of the carbonate fraction has resulted in work being concentrated on insoluble residues. Samples from marl bands and white chalks from Kent, Sussex and France have been analysed to determine their non-carbonate mineralogy. Two methods have been used: X-ray diffraction of fine silt and clay fractions, and EDAX microprobe analysis of a range of coarser grains hand-picked from the greater than 63 µm insoluble residue.

3.3.2 Previous work on marls

Mortimore (1979) analysed insoluble residues from different chalk types (including marl seams) found in the Shoreham to Seaford area of Sussex. He found that all his samples (including those from marl seams) consist predominantly of illite with subordinate kaolinite.

Robinson (1984) described insoluble residue results from samples taken across a marl seam in the North Downs. He found that the dominant clay minerals are smectite and illite, and the percentage of the two varies such that the marl seam has a much higher percentage of smectite than the white and nodular chalk above and below. He also noted the presence of heulandite-clinoptinolite zeolites in a sample 10 cm above the marl seam, and from samples between 10 cm and 60 cm below it. He did not find zeolites within the marl seam.

Pacey (1984) found that insoluble residues of marl seams in the Chalk of Lincolnshire and Yorkshire are dominated by a well crystallised smectite

with an interlayer spacing of 12Å to 15Å. He found no illite but did find subordinate quantities of quartz, feldspar and carbonate apatite. He noted that the mineralogy of white chalks is similar to that of the marls, but they also contain notable quantities of illite.

3.4 FINE SILT AND CLAY FRACTION

3.4.1 Localities sampled

Samples of marly chalk from Middle and Upper Turonian marl bands at Langdon Stairs and Akers Steps (Dover), Caburn Pit, Southerham Works Pit and Beachy Head (Sussex), and Puys (France) were collected and analysed. Samples of white chalk were collected from above and below selected fresh marls at Beachy Head and Puys in order to compare mineralogies.

3.4.2 Method

Acid insoluble residues were produced by dissolving approximately 20 g of chalk in 250 ml of 1M acetic acid. The residue was filtered and washed with de-ionised water before being centrifuged for 5 minutes to separate out any coarser material. Orientated clay mounts were prepared on glass slides using the multiple smear method of Croudace and Robinson (1983). The residues were analysed using a Siemens D500 X-ray diffractometer (School of Earth Sciences, Thames Polytechnic; Cu Kα radiation, 40kV, 30mA). Copies of the traces produced can be seen in Figures 3.1-5.

3.4.3 Results

a) New Pit Marls, Beachy Head (see Figure 3.1)

The mineralogy of all six samples is similar to that reported by previous authors with the exception of Mortimore (1979). The dominant peak is found between 14.96Å and 15.49Å, upon heating to 300°C the peak is found at 9Å, and after glycolation it occurs at 17Å. The peak represents the 001 plane of a smectite, a small peak at 1.49Å indicates that it is dioctahedral. A further peak emerges between 10.04Å and 9.92Å, and is unaffected by either heating or glycolation, and represents the 001 plane of a dioctahedral mica of the illite group. A much smaller peak can be seen

between 7.08Å and 7.13Å, indicating the presence of a small amount of kaolinite. Quartz is found in most samples with a weak to medium peak at 4.27Å (100). A large peak at 3.34Å represents the superimposition of quartz (101) and illite (003). Traces of carbonate apatite occur in some samples, indicated by small peaks at 2.83Å and 2.69Å. Evidence of incomplete dissolution of some samples is demonstrated by the presence of a low, broad calcite peak around 3.05Å to 3.12Å.

The size of the smectite and illite peaks increase on entering the marl, possibly due to an increase in the amount of material on the slide and better orientation. A semi-quantiative indication of the amount of smectite and illite present can be calculated from the 001 peaks using the formula:

$$\text{Peak height} \times \text{width at half peak height}$$

Comparisons of the ratio of smectite to illite between samples can be made using the formula:

$$\frac{\text{Peak height} \times \text{width at half peak height of smectite}}{\text{Peak height} \times \text{width at half peak height of illite}}$$

The smectite:illite (S/I) ratios for the six samples are:

	S/I	
	New Pit 1	New Pit 2
Above marl	10	10
Marl	16	17
Below marl	9	8

These results show similar smectite:illite ratios for the white chalks above and below the marl seams and slightly higher ratios within the seams, indicating a slight increase in the proportion of smectite.

b) Sussex Marls (See Figures 3.2 and 3.3)

Samples of upper Lower, Middle and Upper Turonian marls were collected from disused pits around the edge of Mount Caburn (near Lewes). The observed peaks are similar to those from Beachy Head (above), however kaolinite was only detected in one sample (Malling Street Marl 1).

The smectite:illite ratios are illustrated below, a stratigraphic plot of the variation can be seen in Figure 3.6.

Smectite:illite ratios of marls and white chalks from Sussex, Kent and France

	Marls			White Chalk
	Sussex	Kent	France	France
Lewes	128		245	8
Bridgewick 2	56	43		
Bridgewick 1	45	64	139	7
Caburn	62	43	111	12
Southerham 2	22	18		
Southerham 1	141	88	393	
Glynde 1 [Caburn]	129	182	25	10
New Pit 2	24	11	19	15
New Pit 1	14	10	10	
Malling Street 2	15			
Malling Street 1	9	7		
Gun Gardens Main	16			
Gun Gardens 3	10			
Gun Gardens 2	18			
Gun Gardens 1	11			

c) Kent Marls (Figure 3.4)

Middle and Upper Turonian marls from Langdon Stairs and Akers Steps (Dover) have been analysed. Illite and smectite are the only two clay minerals present, additional phases include carbonate apatite, quartz and undissolved calcite. As with the Sussex samples, smectite is present in considerably larger quantities than illite. The smectite:illite ratios are documented above and illustrated stratigraphically in Figure 3.6

d) French Coast (Puys) Marls (Figure 3.5)

Samples were collected from all accessible Middle and Upper Turonian marls along the coast to the northeast of Puys. Because of wave-washing, both marls and white chalks are clean and unaffected by sub-aerial weathering, enabling semi-quantitative comparison of their mineralogies.

The mineral suite recorded differs from that noted in the Sussex samples. Kaolinite is completely absent, and additional peaks at around 9.02Å, 7.96Å,

3.97Å and 3.91Å, indicate the presence of small quantities of clinoptinolite in all but one sample (Bridgewick Marl 1). Smectite dominates the assemblage in both white and marly chalks. The smectite:illite ratio of adjacent white and marly chalks is fairly similar at the level of the New Pit Marls, but higher marls appear considerably enriched in smectite. The S/I ratios of the collected samples are illustrated above, and stratigraphically in Figure 3.6.

3.4.4 Discussion of results

a)Composition variations

Although collected from nearby localities the Sussex data differs from that presented by Mortimore (1979), because smectite occurs in large quantities in all samples (agreeing with earlier work by Weir and Catt (1965)). It is difficult to propose a sedimentary or diagenetic explanation to account for this phenomena, and therefore the validity of Mortimore's data must be questioned.

The presence of kaolinite in some lower Middle Turonian samples from Sussex has also been reported by Mortimore (1979). Kaolinite in the Lower Chalk is believed to be of detrital origin (Jeans, 1968), a similar explanation is likely for the traces found in the white chalks and marls of the Middle Chalk. Its absence from much of the succession may be related to the type of weathering which adjacent land masses were undergoing at the time (Chamley 1989, p453) which resulted in a change in the clay minerals produced.

Clinoptinolite was only found in white and marly chalk samples from the French coast, Robinson (1984) has however reported it from white chalks above and below Malling Street Marl 1 in Kent. Because there are at least two possible ways that clinoptinolite can be formed in the marine environment (see above), a definitive statement as to its origin cannot be made. However, as biogenic opal CT was probably present across the whole of the Basin (Clayton, 1986), and as clinoptinolite is only found in any quantity on the French coast, it is possible that its presence indicates a small but continuous input of volcanic material into the southeastern part of the Basin, and a much more occasional input into other areas. Importantly, the input appears independent of marl band formation.

b) Stratigraphic variation in marl band mineralogy

Although the smectite:illite ratios must be treated with some caution because of the semi-quantitative way in which they have been calculated, results from Kent, Sussex and France all show similar stratigraphic patterns (see Figure 3.6) which are in close agreement with aluminium normalized potassium results (see geochemistry). Up to New Pit Marl 2 (Glynde 1 in France) smectite:illite ratios are low, values increase sharply around Glynde/Southerham 1 before falling back at Southerham 2/Caburn, values then show an erratic upwards increase.

In slightly saline water, clay minerals have specific settling rates related in part to their ability to flocculate, Whitehouse *et al.* (1960) has shown that smectite settles approximately ten times slower than either illite or kaolinite. Gibbs (1977) study of the western Atlantic off the Amazon river showed that the kaolinite, illite and smectite supplied by the river have different size distributions (smectite $\bar{x}$ = 0.4 μm, kaolinite $\bar{x}$ = 1-2 μm, illite $\bar{x}$ = 2-4 μm), and he argued that a simple physical size segregation would produce a clay mineral segregation upon deposition. Both the above studies show that smectite remains in suspension far longer than either illite or kaolinite, and will therefore be transported further. Hence, clays with a higher smectite:illite ratio are likely to have been deposited further from source, or have been transported at lower current velocities which permitted sedimentation of the heavier clays to take place.

The sea level curve of Hancock and Kauffman (1979; see also Hancock, 1989) shows that the Glynde and Southerham Marls occur during a major transgression, and this is supported by the high smectite:illite ratios of these marls. A major regression commenced shortly afterwards and continued until the late Turonian (ending slightly after the formation of the Lewes Marl). This is again supported by the smectite:illite ratios which show a marked decrease around the Southerham Marl 2/Caburn Marl, and only show any significant increase at the level of the Lewes Marl. The slight variability in the smectite:illite 'transgressive' peak (Glynde and Southerham 1 in Sussex, Glynde in Kent, Southerham 1 in France) may reflect local variations in current velocity, controlled in part by proximity to the edge of the Basin. Although, according to Hancock and Kauffman, the transgression in which Glynde and Southerham occur started in the early Turonian, the low smectite:illite ratios of the New Pit and older marls seems to contradict this. There is however good evidence that the New Pit Marls were formed during periods of relatively high current activity, as at

many localities one or the other is underlain by a prominent erosion surface. Likewise, many of the older marls are found overlying surfaces or occur within nodular units (see Appendix 2), both of which imply increased current activity (see Sedimentology).

c) Comparison between the mineralogy of white and marly chalks

The results from both Beachy Head and France demonstrate clearly that there are no gross mineralogical differences between white and marly chalks. All samples contain smectite and illite, and even 'local' minerals such as kaolinite and clinoptinolite occur in both white and marly chalks.

Although smectite:illite ratios must be treated with some caution because of the semi-quantitative way in which the numbers have been calculated, smectite:illite ratios of samples taken across the New Pit Marls at Beachy Head indicate that they contain a slightly higher proportion of smectite than adjacent white chalks. Evidence from France, although slightly incomplete, agrees with this, and shows smectite:illite ratios of white chalks remaining relatively constant, whilst marls show an increase up-section (Figure 3.6). Accepting that the smectite and illite present in white and marly chalks is detrital in origin (as implied by sedimentological and rare-earth element studies), then white chalk values may represent a 'background' homogenized mixture of clays which, through repeated reworking and slow deposition, are not greatly influenced by sea level fluctuations or distance from source.

Recent work has demonstrated the importance of aeolian transported material in Atlantic sediments (Pye, 1987; p171); a slow but constant input of illite-rich aeolian sediment would affect the composition of white chalk far more than marls because of the faster deposition of the latter. Supporting evidence for this is given by the frosted and pitted nature of many quartz grains (see Plate 14, and below).

The illitization of smectites in sea water has often been proposed (e.g. Grim and Johns, 1954; Latouche, 1972), and could account for the observed differences between white and marly chalk. More recent work (e.g. Schultz, 1978; Środoń, 1984) has questioned these proposals, demonstrating that adjacent freshwater and marine facies show negligible differences in clay mineralogy, and that the percentage of potassium available in sea water is too low to increase the amount of illite. Importantly, the rare-earth element patterns for white and marly chalks are very similar, both indicate

that the clay minerals are detrital and have undergone little or no alteration in the marine environment (see Geochemistry).

d) Comparison with marls of the Northern Province

Pacey (1984) only reported the presence of smectite in marls of the Northern Province which suggests that they are located further from source than those of the Anglo-Paris Basin. The absence of nodular chalks and hardgrounds in the Northern Province is often taken as good evidence that it is a deeper water facies (C.J. Wood *pers. comm.*), supporting the clay mineral evidence. It cannot however be discounted that the prime reason for the difference in mineralogy is that the clays of the Northern Province are derived from a completely different source to those of the Anglo-Paris Basin.

3.5 COARSE FRACTION

3.5.1 Method

500g of each sample was dissolved in 1M acetic acid and the residue passed through a 63 µm sieve (v. fine sand). Material trapped in the sieve was oven dried, weighed and stored in stoppered bottles.

3.5.2 Results

a) New Pit Marls, Beachy Head

Samples were collected across both New Pit Marl 1 and New Pit Marl 2 at Beachy Head. The quantity of material after dissolution varied slightly between samples, but was always less than 2 g.

All the samples contain quartz and apatite, and all but two (from below N.P. 2 and within N.P. 2) contain either pyrite or limonite. Approximate quantities of the minerals vary: quartz 5-50%, apatite 30-90%, pyrite/limonite 0-40%, but there is no predictable pattern. Grains are usually between 60 and 250 µm in size. Quartz grains vary in shape from angular to sub-rounded, the latter often show slight frosting and/or pitting. Apatite grains are a gold- to red-brown colour, and usually have

an angular, platy form. Both the pyrite and limonite grains have an unpredictable, irregular shape.

b) Southerham Marl 1, Eletot.

This marl was chosen because even at outcrop it is below the water table, helping to prevent oxidation of some minerals. The residue from a 1kg sample of marly chalk revealed a slightly more complicated assemblage of minerals than that from Beachy Head. Determination of the composition of many of the grains was carried out using a scanning electron microscope fitted with EDAX (based at Thames Polytechnic, Woolwich) Photographs of many of the grains can be seen on Plates 14 and 15. Although again dominated by a mixture of phosphate and quartz, fresh pyrite is more conspicuous and glauconite is present in small amounts. In addition to these minerals, occasional spherical grains of a dark brown material can be found, isolated examples of which appear to have a short sinuous 'tail'. EDAX microprobe of these grains revealed that they are organic, and similar to those described from the Cretaceous-Tertiary boundary by Hansen *et al.* (1986)

3.5.3 Discussion of results

Although only a small study was undertaken, the results show that the coarse fraction is dominated by quartz, apatite and pyrite/limonite; fresh pyrite and glauconite are also found in less weathered samples. There does not appear to be any correlation between marl seam formation and coarse fraction mineralogy.

a) Origin of the quartz

Spears (1979) and Pacey (1984) both suggested that all quartz in chalks is detrital. In contrast, Weir and Catt (1965) argued that the delicate structure of many quartz grains precluded this, and therefore at least part of it is authigenic. Robinson (1984) demonstrated that quartz occupies a relatively higher proportion of the insoluble residue in marls when compared to white chalks above and below, and he proposed that the increase in quartz and smectite may be interrelated.

No evidence was found in this study which supported an authigenic origin for any of the quartz, and it seems more likely that it is all of detrital origin. The well rounded and frosted nature of many of the grains (see Plate 14) may signify that the grains underwent aeolian transportation, as river abrasion may 'defrost' grains to produce a polished surface (Pettijohn *et al.*, 1973, p85; see also Hancock, 1975b, p109). This adds support to the proposal that some of the clays were transported by air (see above).

b) Origin of the apatite

EDAX microprobe examination of grains indicated that the apatite is carbonate-rich, and therefore similar to that found in the clay and fine silt fraction. Although the shape of many grains examined gave little information as to their origin, fish scales and teeth could occasionaly be recognised, supporting a vertebrate origin for the phosphate.

c) Origin of the pyrite, glauconite and limonite

All three minerals are likely to be of authigenic origin, with the limonite being derived from weathering of the other two. Many glauconite grains have a form similar to that of the inside of a Foraminifera test, implying that they provided a suitable environment for its formation. Pyrite probably formed during early diagenesis in the sulphate reduction zone (Curtis and Spears, 1968).

d) Origin of the organic spherules

Hansen *et al.* (1986) proposed that organic spherules found at the Cretaceous-Tertiary boundary were derived from the green algal group Prasinophyta. Although detailed examination of the spherules collected during the present work was not undertaken, it seems likely that they have a similar origin.

3.5.4 Comparison with the Northern Province

Pacey (1984) produced a series of scanning electron microscope photographs of minerals which he proposed were of volcanic origin. He produced no chemical evidence to support these claims and seems to have based his

arguments solely on their texture. Many of the minerals examined as part of the present work had similar textures to those illustrated by Pacey, but EDAX microprobe examination revealed that they were usually crystals of quartz or limonite which are most easily interpreted as being either detrital or authigenic in origin. Using the information gained during my study, the photographs of grains presented by Pacey can be reinterpreted as follows: figure 5 is a grain of fish-derived carbonate apatite; figure 6a is an angular grain of quartz; figure 6b is a fragment of clay which was not removed during the separation process; and figure 6c consists of two well rounded quartz grains. It would therefore appear that coarse grained minerals which would support a volcanogenic origin for the marls of the Northern Province are no longer preserved or were not deposited in the first place.

4. PETROGRAPHY

4.1 SUMMARY

The carbonate petrography of marls and adjacent white chalks is reasonably similar. The number of coarse fragments may decrease within a marl due to dilution by the clays, or it may increase if bioturbation causes the incorporation of winnowed material from an underlying erosion surface.

Coarse particle alignment at right angles to the compression direction occurs within marls but not in white chalks due to the former's ability to remain in a semi-plastic state during the early stages of burial.

Crushed or deformed grains are more common within marls due to the increased number of grain-to-grain contacts brought about by the alignment of particles.

Evidence of carbonate dissolution can be recognised in coarser grained marls by the presence of thin anastomosing networks of wispy clay seams.

4.2 INTRODUCTION

Chalks are best described as biomicrites (after Folk, 1959), or as mudstones, wackestones or packstones (after Dunham, 1962) depending on the percentage of coarse carbonate grains. Most consist of foraminifera, calcispheres and fragments of macrofossils such as bivalves and echinoderms, set in a micritic, coccolith-rich matrix. Most also contain small amounts (less than 1%) of silt-sized quartz and occasional fragments of vertebrate derived calcium phosphate (see Mineralogy). Chalks composed largely of bryozoa have been described from Denmark (Håkansson *et al*, 1974).

Whilst the petrography of white chalk has been documented by several authors (Jukes-Browne and Hill, 1903, 1904; Wolfe, 1968; Kennedy and Garrison 1975; Quine, 1988), marls have received little attention. The aim of this Section is to compare the petrography of marls and adjacent white chalks, and to compare the petrography of different marl seams. Three examples reflecting the range in form of marls (with white chalk above and below, resting on a surface, and within nodular chalks) can be used to

summarise the features observed, and are described below. Photomicrographs of all three examples and their associated white chalks can be seen in Plates 16, 17 and 18.

4.3 RESULTS

4.3.1 New Pit Marl 1, Beachy Head (white chalk above and below).

The marl is best classified as a mudstone as the number of coarse grains is relatively low. Larger grains identified include calcispheres, fragmented and whole Foraminifera, and occasional fragments of macrofossils. Clay and carbonate are usually evenly mixed in the micrite, although there is some evidence of post-burial pressure solution of some carbonate (see Plate 16). Specimens contain no examples of the anastomosing network of clay seams observed in New Pit Marl 2 (see below).

Soft white chalks from above and below the marl are similar but contain more coarse carbonate grains than the marl. Calcispheres dominate over Foraminifera in samples from both above and below the marl.

4.3.2 New Pit Marl 2, Beachy Head (resting on a surface).

This is best classified as wackestone containing numerous calcispheres, broken and whole Foraminifera, and fragments of macrofossils. Clays are seen to be concentrated in thin anastomosing networks, reflecting some carbonate dissolution during diagenesis. The edges of large particles at right angles to the compression direction acted as foci for dissolution, as illustrated by the concentration of clay wisps (see Plate 17). Many of the coarser particles display at least weak alignment at right angles to the compression direction; as bioturbation is likely to have produced a random orientation, the alignment is presumably derived from particle rotation during de-watering and compaction of the clays. Some fracturing of thin-walled Foraminifera tests can be observed, especially when in contact with other large particles

The white chalks above and below the marl are best classified as mudstones as the concentration of coarse grains is noticeably lower than that of the marl. The composition of the coarse fraction appears to change slightly,

becoming richer in calcispheres. Particle orientation is far more random than in the marl, implying that the presence of clays, with their ability to retain water during the early stages of compaction, is a controlling factor.

4.3.3 Bridgewick Marls, Langdon Stairs (nodular chalks above and below).

Both marls have a variable texture, alternating between a wackestone and a packstone, and contain the usual assemblage of fragmented and whole forams, calcispheres, and fragments of macro fauna up to 1 mm in diameter. Alignment of the coarser fragments at right angles to the compression direction is common. There is some evidence of an anastomosing clay network similar to that observed in New Pit Marl 2, but the very coarse nature of both marls partially disguises it or has inhibited its development.

Samples of nodular white chalk from above and below the marls also have a wackestone/packstone texture and have a similar coarse carbonate grain composition to the marls (but see discussion, Plate 18). As with New Pit Marl 2, they do not display a marked alignment at right angles to the compression direction. Crushing and deformation of grains (especially thin-walled Foraminifera) is seen in both white chalks and marls, but occurs slightly more frequently in the marls.

4.4 DISCUSSION AND CONCLUSIONS

From the above observations it appears that the carbonate petrography of marls and adjacent white chalks is reasonably similar, and that the composition of adjacent white chalks strongly influence that of the marl:

1. Where soft white chalks occur above and below a marl a slight decrease in the percentage of coarse fragments is observed within the marl, reflecting dilution of the white chalk through the addition of clays.

2. Where coarse nodular chalks occur above and below, the marl has a similar composition, although fragments may be slightly more crushed or deformed.

3. Marls overlying prominent erosion surfaces are usually coarser than white chalks above the seam and below the surface.

Incorporation of winnowed coarse grains from the surface through the action of bioturbating organisms appears the most likely explanation for this (see Sedimentology).

The alignment of particles only seems to take place within marls, whilst white chalks appear to have a near-random orientation. This is probably a reflection of the ability of clays to remain semi-plastic during early compaction (see Sedimentology), allowing rotation of coarse particles to minimize the compactional stress imposed upon them. White chalks are likely to have de-watered at a much faster rate because of their lower clay content, preventing particle rotation.

The crushing and deformation of grains is much more apparent in packstones than in wackestones, and rarely occurs in mudstones. This is presumably a reflection of the ability of the sediment mass to deform rather than act in a rigid manner. An increase in the proportion of coarse debris (calcispheres and foraminifera) is likely to cause the sediment to act in a more rigid manner, especially where they are in contact, and will in turn induce crushing and deformation. It may occur more commonly in marls because of the ability of coarse grains to move and rotate during early compaction, increasing the number of grain-to-grain contacts.

The presence of anastomosing clay networks in New Pit Marl 2 and the Bridgewick Marls is undoubtedly a legacy of carbonate dissolution during diagenesis (see also Geochemistry). Their absence from white chalks above and below the marls implies that relatively high concentrations of clay must be present for them to form (see also Sedimentology). In all three examples the marl seam rests above a unit of harder chalk (a nodular omission surface in the case of New Pit Marl 2, and thick nodular units in the case of the Bridgewick Marls), it is likely that these relatively firm units resisted compaction, causing stresses to be concentrated in the softer marly unit above, further enhancing dissolution. The absence of such networks from New Pit Marl 1 is probably due to a combination of lack of coarse fragments and the absence of firmer than normal chalk beneath the seam, both features allowing more even compaction of the whole unit.

5. MICROPALAEONTOLOGY

5.1 INTRODUCTION

A limited amount of micropalaeontological data has been collected in an attempt to see if there are any changes in the fauna or flora associated with the formation of a marl band. The impetus for this part of the study was provided by three papers: Ernst (1978, 1982), and Curry (1982), all of which argue that changes in the foraminiferal assemblage indicate that marls were formed as a result of calcium carbonate dissolution on the sea bed. The foraminiferal data discussed below was kindly provided by Dr. Paul Leary, the calcareous nannofossil data by Dr. Jackie Burnett, and the dinoflagellate cyst data by Ms. Meriel Fitzpatrick, all of whose assistance is gratefully acknowledged.

5.2 FORAMINIFERA

5.2.1 Results

Samples were collected from above, below, and within three fresh marls below the Chalk Rock at Burghclere; field observations and geochemical analysis of samples of the marls (see Section 7.6.2ci) indicates that they are the lateral equivalents of New Pit Marls 1 and 2, and Glynde Marl 1 [Caburn]. The results obtained are presented in Figure 5.1, and have been discussed at some length in Leary and Wray (1989) (see enclosure). The data shows that the planktonic:benthonic ratio decreases markedly within the marl, and that the surface dwelling, non-keeled, forms are reduced in abundance the most. Changes in the benthonic population also occur with epifaunal groups gavellinellids and lenticulinids) noticeably decreasing in number relative to the infaunal groups (tritaxids, marssonellids, eggerellinids and arenobuliminids). Dissolution is more marked on foraminifera tests from within the seam.

5.2.2 Discussion

The results obtained are in broad agreement with those obtained by Ernst (1978, 1982) and Curry (1982). As already discussed (see Sedimentology), it seems likely that marl seams were often 'diluted' with carbonate from above and below through the action of burrowing organisms; of the three marls examined, Glynde Marl 1 has probably undergone least bioturbational alteration (see Section 2.5.3). The effects of bioturbation must also be taken into consideration when examining Ernst's data, which shows a gradual transformation from the white chalk assemblage to the marl assemblage as the seam is approached. Although he proposed that the pattern reflected a gradual increase in carbonate dissolution due to increased burial of organic material, it is more likely to be a result of sampling a mixture of white chalk and marl-filled burrows which have been preserved as flasers above and below the seam (see Sedimentology).

The observed change in the benthonic fauna is consistent with the rapid introduction of non-carbonate sediment into the water column. Upon deposition this material would have had a significant effect upon the epifaunal taxa due to the sudden change in substrate, whilst having little effect on the infauna. This is best seen in Glynde Marl 1 where, because of its lack of bioturbational alteration, the epifaunal gavellinellids and lenticulinids all but disappear.

Changes in the planktonic assemblage and in the planktonic/benthonic ratio cannot be explained as easily due to the possibility of dissolution. Corrosion of tests increases markedly within marls, and geochemical analysis has shown that carbonate dissolution occurs within marls (Section 6.3). Because foram test thickness generally increases with water depth (Leary *in* Jarvis *et al.*, 1988a), dissolution will have a proportionately greater effect on near-surface planktic forms. This combination of increased evidence of dissolution within marl seams and differences in test thickness between different groups makes any meaningful comparison of variation either within the planktonic forams or between the planktonics and benthonics highly speculative if not impossible.

Leary and Wray (1989) proposed that changes in the foraminiferal population were related to an influx of volcanic ash. This proposal was based on the assumption that dissolution had affected both marls and chalks to the same degree, and on the conclusions of earlier workers in Germany (for example Valeton, 1959, 1960) and England (Pacey, 1984; Robinson, 1984). The evidence presented in this thesis indicates that the

clays are detrital, although the effect on the benthos is likely to be similar.

5.3 DINOFLAGELLATE CYSTS

5.3.1 Results

A limited study using sub-samples of those used for the foraminiferal work has been carried out, and the results obtained are presented in Figure 5.2.

5.3.2 Discussion

None of the samples were particularly rich in cysts. The total number per slide is seen to increase within the marls, although the amount of increase is very variable, and inversely proportional to the amount of clay in the marl seam (Glynde Marl has the most clay-rich seam, New Pit Marl 1 has the least). The number of cysts per gram of rock is much more variable, with only one marl (New Pit 1) showing enrichment.

The variable nature of this data means that any conclusions are tentative. It does not however appear that marl formation effected cyst production in any predictable manner, assuming that the level of post-depositional preservation has remained constant.

5.4 CALCAREOUS NANNOFOSSILS

5.4.1 Results

A series of samples were collected across New Pit Marls 1 and 2 at Beachy Head. The nannofloras are generally poorly preserved, breakage, slight etching and calcitic overgrowths were observed. No differences in species size was observed.

Both marl seams were slightly more diverse than the white chalk above and below, but the overall diversity is low (37-44 species). The results are illustrated graphically in Figure 5.3. Three species show slight but

consistent variations across both marl seams: *Eprolithus moratus* increases, and both *Helicolithus trabeculatus* and *Tranolithus orionatus* decrease in abundance within the marl seam. Other species show a variation across one or the other seam: *Biscutum ellipticum* and *Retecapsa crenulata* both decrease in number in New Pit Marl 1, whilst *Eprolithus floralis* increases in number in New Pit Marl 2.

5.4.2 Discussion

Although some minor variations are observed when passing from white into marly chalk, there is no clear-cut, overall pattern to the changes. Small scale changes may have been masked by bioturbation, but there is no significant change in the composition of the nannoflora when passing from white into marly chalk.

5.5 SUMMARY OF MICROFAUNAL DATA

Of the three groups studied, only the foraminifera show consistent variations between white and marly chalk. Although changes in the planktonic foram assemblage may be due to clay-enhanced dissolution within the marl seam during compaction, it is unlikely that a similar process caused the observed variations in the benthic assemblage. Changes in the benthic population are consistent with an influx of non-carbonate rich material which markedly changed the bottom conditions (causing a decrease in the epifauna), but had little effect on the infauna.

Neither the dinoflagellates nor the calcareous nannofauna show a consistent variation when passing from white to marly chalk. Although bioturbation may have masked any small-scale changes, it appears that the creation of a marl seam had little effect on either group.

6. GEOCHEMISTRY

6.1 SUMMARY

Major element variations across New Pit Marl 2 (at Beachy Head) reflect an increase in the amount of non-carbonate material within the sediment. Most trace element patterns mimic those of the major elements associated with the clay fraction although some also show evidence of being present in authigenic minerals.

Statistical analysis and aluminium normalised plots of a series of samples across New Pit Marl 2 at Beachy Head show that most of the major and trace elements are associated with the clay fraction. The relative concentration of these elements remains similar between the white and marly chalk, implying that there is no gross mineralogical difference between white and marly chalk, simply a change in the relative proportions of the carbonate and non-carbonate phases. Aluminium normalised potassium results vary slightly across the marl seam, indicating a small change in the proportion of illite relative to smectite.

Sr/Ca and Mn/Ca ratios from the carbonate phase show that a small amount of dissolution has occurred within the marl seam, and that reprecipitation occurred above the seam.

Rare-earth element patterns from New Pit Marl 2 and the white chalk above and below are similar, slight variations between them being due to fluctuations in the percentage of carbonate. Shale normalised patterns are sub-horizontal, indicating that the clays are of detrital origin. Results from Turonian marls higher up the sequence show similar patterns.

Stable isotope results show that $\delta^{13}C$ does not vary across individual marl seams, but there is a stratigraphic variation as demonstrated by previous authors. $\delta^{18}O$ does vary across all marl seams analysed, becoming up to 1‰ heavier within the marl. Although there are several possible reasons for this, the most likely appears to be that the formation of a marl seam was accompanied by a fall in sea water temperature. Calculations suggest that the fall may have been as much as 4.5°C in the case of New Pit Marl 2 at Beach Head.

Total organic carbon results across New Pit Marl 2 show no significant variation, implying that the formation of marl seams was not accompanied by increased burial of organic .debris.

Stratigraphically, the proportion of clay within marl seams appears to decrease, although this may simply be a reflection of the degree of bioturbation that the sediment underwent. The K_2O/Al_2O_3 ratio shows a sharp decrease around the Glynde Marl, reflecting a change in the illite/smectite ratio caused by the middle Turonian transgression; its subsequent increase being related to the late Turonian regression. Normalising the clay-associated elements against both aluminium and potassium indicates that some of the trace elements are associated with the illite (Ba, Sc, V, Ti?), whilst others are associated with the smectite (Li, Zn, Cu?, Zr?). Yttrium appears to be associated with both the phosphate and clay phases.

6.2 INTRODUCTION

6.2.1 Previous work

Previously published geochemical data on chalks tend to be generalized (Hancock, 1975a; Pitman, 1978; Spears, 1979), or concentrated on overall long-term trends in particular elements (Pomerol, 1983), taking little account of the detailed sedimentology of the beds investigated. More recently, some workers have used geochemistry to explain sedimentary and diagenetic features such as lithification (Jeans, 1980), phosphatic hardgrounds (Jarvis, 1980c), pelletal phosphates (Pacey, 1985) and flints (Clayton, 1986). Diagenetic studies of the lithification of chalk in the North Sea (Jørgensen, 1986, 1987) and chalk in Yorkshire and Northern Ireland (Mimran, 1978) have also made use of geochemical analyses, particularly of elements associated with the carbonate fraction. Pacey (1984) is the only worker who has specifically studied the geochemistry of marl seams, concentrating on examples from Yorkshire and Lincolnshire.

6.2.2 Analytical methods

In order to obtain as complete an analysis as possible, several different techniques have been employed. These include: fusion with lithium

metaborate, acid digestion using hydrofluoric and perchloric acids, acid digestion using acetic acid, and acid digestion using hydrofluoric and perchloric acids followed by separation using ion exchange columns. For details of the above methods see Appendix 3.

6.2.3 Chemical considerations

Bulk rock analysis was undertaken on most samples in preference to other forms of analysis (such as separation and analysis of the insoluble residue), as it was felt that attempts to separate the different mineral phases would lead to unknown errors, for example: even mild acids are capable of stripping weakly bonded elements from clays (Newman and Brown, 1987).

In order to explain changes in chemistry and how they relate to mineralogy certain considerations and assumptions need to be made. Below is a list of the major and trace minerals often found in marly chalk (see mineralogy). From this data it is possible to predict with some accuracy where many elements are concentrated (data from Deer *et al.* 1966).

Major Minerals in Marly Chalk	
Calcite	$CaCO_3$
Carbonate-apatite	$Ca_5(PO_4,CO_3OH)_3(F,OH)$
Illite	$K_{1-1.5}Al_4[Si_{7-6.5}Al_{1-1.5}O_{20}KOH)_4$
Quartz	SiO_2
Smectite	$(½Ca,Na)_{0.7}(Al,Mg,Fe)_4(Si,Al)_8O_{20}(OH)_4.nH_2O$
Trace Minerals in Marly Chalk	
Clinoptinolite	$(Ca,Na_2)[Al_2Si_7O_{18}]6H_2O$
Glauconite:	$(K,Na,Ca)_{1.2-2.0}(Fe,Al,Mg)_4[Si_{7-7.6}Al_{1-0.4}O_{20}KOH)_4.nH_2O$
Kaolinite	$Al_4[Si_4O_{10}KOH)_8$
Limonite	$FeO.OH.nH_2O$
Potassium feldspar	$(K,Na)[AlSi_3O_8]$
Pyrite	FeS_2

The above list shows that calcium is only present in large quantities within calcium and carbonate-apatite, whilst aluminium occurs within clay minerals and potassium feldspar. Potassium is primarily concentrated in illite, and may also be present in glauconite and potassium feldspar. Most of the other elements occur in several mineral phases making interpretation of their geochemical patterns difficult.

6.3 RESULTS

6.3.1 Introduction

In order to obtain as much detailed information as possible, one marl (New Pit 2, Beachy Head) has been selected for detailed geochemical analysis using a series of different techniques. The results obtained have then been used to assist in the interpretation of stratigraphic variations in marl seam composition using a series of samples from Sussex.

6.3.2 Variations across an individual marl band

In order to demonstrate the chemical variations which occur across a marl band, a series of samples were collected across New Pit Marl 2 at Beachy Head. This particular marl was chosen because it is not associated with a nodular unit (which would introduce further complexities due to the presence of early diagenetic cement), and it is well exposed and unweathered. A series of analyses have been carried out, the results of which can be found in Appendix 4.

a) Summary of results

i) Major elements (Figure 6.1)

The results for the white chalk samples are in good agreement with the general results presented by Hancock (1975a) and Spears (1979).

Examination of the major element trends suggests that the overriding control on the abundance of individual elements is the relationship between the amount of carbonate and the amount of clay: SiO_2, Al_2O_3, MgO, Fe_2O_3, Na_2O, K_2O and TiO_2 all increase within the marl by factors of between 4

(MgO) and 11 (Al_2O_3), whilst both CaO and Sr decrease. Care must be taken with the interpretation of some elements as they are present within more than one non-carbonate mineral phase (for example SiO_2 occurs in quartz, kaolinite, smectite and illite) and, more importantly, some (including MgO and Fe_2O_3) occur in both carbonate and non-carbonate phases. The manganese pattern requires further investigation, as its near-straight line trend is difficult to reconcile with those of the other elements. A possible explanation may be that redox processes during early diagenesis resulted in the redistribution of manganese within the sediment (Berner, 1980 p136) and the formation of authigenic minerals such as rhodocrosite ($MnCO_3$). As no evidence of such minerals was found during the course of this study (see Mineralogy) this proposal must be treated with some caution. The pattern produced by strontium is also somewhat difficult to interpret: values decrease on entering the marly chalk from below, but remain low (for at least 40 cm) after leaving the marl. The interpretation of both these elements is discussed further in the Section 6.3.2d.

Phosphorus is almost wholly contained within the carbonate-apatite phase. Its sharp increase within the marl indicates a moderate increase in the amount of carbonate-apatite within the sediment.

ii) Trace elements (Figure 6.2)

Trace element patterns tend to mimic those of the major elements. Most trends show an increase within the marl, implying that the majority are associated with the non-carbonate fraction. There are however complications: the concentration of some elements in white chalks is occasionally below the detection limit of the analytical method used; and the elements chromium, copper and zinc all produce very irregular trends. Chromium peaks are observed both within the marl and also in the white chalk close to the base of the sampled section, suggesting that there may be small quantities of a chromium-bearing authigenic mineral within the sediment. Likewise, the pattern for zinc is distorted by two very high anomalous values (one from white chalk and one from marly chalk), again inferring the presence of authigenic mineral phases. Although copper peaks within the marl, the shape of the peak is more irregular than that of most of the other major and trace elements, and may reflect the presence of both 'primary' and authigenic copper containing minerals.

b) Statistical analysis

In an attempt to reconcile some of these problems and to aid interpretation of the data, the analyses were entered into a Statgraphics® statistical package and a correlation matrix produced (see Figure 6.3). The correlation matrix supports the observations made above, and gives much additional information concerning elemental relationships (detailed below).

i) Carbonate phase

Calcium shows a negative correlation with all elements except strontium, and even with the latter the correlation is not ideal, probably due in part to the anomalous values seen above the marl. Manganese, as expected, shows little correlation with either the carbonate or non-carbonate phases.

ii) Clay mineral phase

Major elements associated with the clay phase all show a good correlation with aluminium as expected. Magnesium and iron both show a good correlation with aluminium, implying that the carbonate phase consists of low-Mg calcite and that pyrite and iron oxides are only present in small amounts. The excellent correlation between potassium and the other elements present in the clay phase demonstrates that potassium feldspar is either present in negligible amounts, or that it mimics the clay mineral trend. Additionally, this correlation implies that the illite/(smectite and kaolinite) ratio of the white and marly chalk are similar, and that there is a negligible increase in the proportion of smectite within the marly chalk. Sodium also correlates closely with aluminium, suggesting that it may be one of the important interlayer ions within the smectite.

As expected, most of the trace elements show reasonably good correlations with major elements in the clay phase. The only exceptions to this being chromium and zinc, both of which are likely to be present in additional, authigenic phases (see above). Caution is necessary in the interpretation of the yttrium results as it is likely to be present in the phosphate phase as well (see below). Unfortunately, the correlation matrix cannot be used to differentiate between those elements associated with smectite and those associated with illite because, as noted above, the relative concentration of the two minerals remains reasonably constant.

iii) Phosphate phase

Phosphorus shows a surprisingly good correlation with elements in the clay phase, from which it can be inferred that variations in the amount of carbonate-apatite within the sediment follow reasonably closely those displayed by clay minerals. Plots of Y against Al_2O_3 and P_2O_5 both show good correlations, again suggesting that Y may be present in both phases.

iv) Other mineral phases

Although small quantities of glauconite have been observed within New Pit Marl 2 at Beachy Head, the similarity of its formula to that of illite means that the correlation matrix cannot be used to isolate it. All that can be said is that either it remains proportional to the amount of clay, or that it is present in such small amounts as to make its effect negligible.

Clinoptinolite was not found in samples from Beachy Head (see Mineralogy).

c) Normalised plots

As virtually all the aluminium within chalks is associated with the clay mineral phases (see chemical formulae, Section 6.2.3), the ratio of other elements apparently associated with the clay minerals to the aluminium value of the sample will allow comparison between samples. This process has been carried out on the samples from New Pit Marl 2, and the results are displayed graphically in Figure 6.4.

The plot of K_2O/Al_2O_3, whilst slightly irregular, shows a very slight decrease towards the seam and increases slightly above it, indicating a slight increase in the smectite:illite ratio within the marl. This decrease is also apparent from examination of X-ray diffraction traces (see Mineralogy) and is more marked in marls higher in the succession (see Section 6.3.3c).

The plot of SiO_2/Al_2O_3 can be tentatively used as an indicator of the quartz/clay ratio within the sediments (assuming that the relative proportions of all the clays remain reasonably constant). Therefore, the gradual climb in the SiO_2/Al_2O_3 plot below the marl seam may reflect a slight increase in the proportion of quartz within the sediment. The sharp decrease in the ratio on entering the marl seam suggests that the percentage of quartz (relative to clay) decreases, before gradually returning

to 'white chalk' values above the seam. Overall, this plot implies that the marl seam was formed as a result of an increase in clay deposition which was not mimicked by an increase in quartz.

Plots of MgO/Al_2O_3 and Fe_2O_3/Al_2O_3 show slight decreases on entering the marl, possibly reflecting their presence in more than one phase (Mg in the carbonate phase and Fe in iron oxides).

The plot of TiO_2/Al_2O_3 has an anomalous 'spike' a short distance below the marl which cannot easily be explained. Across the marl, however, there is no apparent variation, demonstrating that the proportion of titanium within the clay fraction remains near-constant.

Although the correlation matrix demonstrated a good correlation between P_2O_5 and Al_2O_3, the aluminium normalized plot shows that a relative decrease in the amount of phosphorus occurs, and in many ways the trend produced mimics that of the SiO_2/Al_2O_3 plot. Therefore it can be concluded that although the amount of phosphate increases within the marl, the increase is not as great as that of the clays.

Interpretation of many of the trace element/Al_2O_3 results is hindered because of the very low values (often below detection limit) encountered within white chalks. Nevertheless, the plots of many of the elements infer that they are likely to be associated with the clay phase (as the correlation matrix demonstrates). Both scandium and vanadium show a good correlation with aluminium, although both plots drop slightly on entering the marl. The trends of copper, lithium and zinc, whilst more irregular or with 'missing' white chalk values, also seem to be associated with the clay fraction. The similarity of the yttrium and phosphorus trends suggests that some of the yttrium occurs in the phosphate. Barium has an irregular normalized plot, possibly because small quantities of it are present in the calcite (Deer *et al.* 1962; p226)). The plots for chromium and zirconium are both difficult to interpret due to 'missing' values, but from the results obtained it seems unlikely that the former is associated with the clay phase, whilst the latter may be.

d) Carbonate associated elements

Figures 6.5 and 6.6 display the results from the New Pit 2samples for a series of elements which were detected in solution after the samples had

undergone an acetic acid digestion. Despite the very gentle nature of this dissolution, it is apparent from fluctuations in aluminium values that small quantities of non-carbonate associated elements are also present; hence some care must be taken in the interpretation of these results (see also Renard *et al.* 1978).

As might be expected, calcium decreases sharply within the marl, a decrease which is mimicked to a certain extent by iron and strontium. Above the marl seam strontium values remain low and only return to a 'white chalk' value at the top of the section. The plot of strontium/calcium ratios demonstrates a similar trend, although a small peak occurs in the centre of the marl seam. As the small peak corresponds with the aluminium peak, it is likely that it represents the presence, in solution, of a small quantity of strontium leached from the clays. The low strontium values above the marl require a different interpretation. Trace element studies on carbonate rocks (see Veizer, 1983 for a review) have shown that diagenetically precipitated calcite will be depleted in strontium relative to the water from which it was precipitated. Therefore dissolution and subsequent reprecipitation of calcite due to pressure solution will result in a lower Sr/Ca ratio in the precipitated calcite when compared to the original (Kinsman, 1969, Baker *et al.* 1982). Hence, it is likely that the lower Sr/Ca values seen within and above the marl indicate that dissolution and reprecipitation of some carbonate has occurred. The marl seam is the most likely source of the carbonate because the presence of clay assists the dissolution process (see Section 2.8.3). The asymmetrical distribution of the diagenetic calcite is to be expected as the main direction of pore fluid movement during compaction is upwards (Lerman, 1979; Berner, 1980 (Figure.9)).

The pattern exhibited by iron is difficult to explain as it appears unaffected by the increase in the proportion of clay (leaching of some iron from the clays might have been expected). Additionally, unlike strontium, its values above the marl remain near constant. Reprecipitated carbonate may be either richer in iron than the source or have similar values (Veizer, 1983); the trend across New Pit Marl 2 indicated that the latter is true in this case.

Studies of Mn/Ca ratios have shown that it behaves in the opposite way to strontium: it is enriched in reprecipitated carbonate (see Veizer, 1983). The Mn/Ca plot shows that values gradually increase below the marl, but directly below the base of the marl a sharp increase occurs, which

continues into the the seam, and is followed by a gradual decrease commencing in the higher part of the marl and continuing in the white chalk above. Whilst the trend within and above the seam supports the diagenetic trend derived from the Sr/Ca results, it is difficult to explain the increase in Mn/Ca values below the seam as they are not supported by a corresponding decrease in Sr/Ca values.

Results for many of the other elements studied (notably Mg, Zn and Ba) must be treated with caution as their trends are similar to that of aluminium, implying that they are likely to have been affected by leaching of elements from the clay fraction.

e) Rare-earth elements

i) Introduction

Despite similarities in chemical behaviour the rare earth elements (REE) can be partially fractionated, providing a valuable guide to the mineralogy, provenance and diagenetic history of sedimentary rocks (Fleet, 1984). Previous workers, studying the distribution of the REE between carbonate and non-carbonate phases in limestones and coccolith oozes, have concluded that a high proportion of the REE are to be found within the non-carbonate fraction (Parekh *et al.* 1977; Tlig and Steinberg, 1982; McLennan *et al.* 1979; Fleet, 1984). Carbonate phases generally contain low amounts of REE and tend to have trends similar to that of sea water (Elderfield *et al.* 1981). The only exception to this is phosphatic fish debris, which scavenges REE from sea water (Arrenhius *et al.*, 1957; Bernat, 1975; Elderfield *et al.* 1981), and displays a sea water signature (Fleischer and Altschuler. 1969).

Numerous workers have demonstrated that the REE patterns produced by shales derived from continental weathering are very similar (Minami, 1935; Haskin and Gehl, 1962; Wildeman and Haskin, 1965; Haskin *et al.* 1966; Piper, 1974), being enriched in light REE (La to Sm; LREE) relative to the heavy REE (Gd to Lu; HREE) when normalized to chondrites. Weathering and erosion result in very minor amounts of REE going into solution, as only a few percent of the REE entering the ocean are dissolved (Martin *et al.* 1976). The overwhelming concentration of the REE in the detrital fraction of transported material, rather than the dissolved portion, means that the REE pass from weathering to deposition almost exclusively without taking

part, en route, in any significant chemical processes (Fleet, 1984), and will retain a shale REE pattern. In contrast, authigenic clays, developed in sea water, will display a REE pattern similar to that of sea water. Likewise, clays derived from the submarine weathering of volcanic material will display an anomalous REE trend relative to the shale trend, being markedly depleted in cerium and enriched in the HREE relative to the LREE (Piper, 1974; Fleet, 1984). All the above implies that REE patterns may give valuable information regarding the source of the non-carbonate fraction within both marl bands and white chalk.

ii) Results

Chondrite normalized results from samples collected below, within and above New Pit Marl 2 (see Figure 6.7) show a sloping pattern from left to right as expected (Jarvis and Jarvis, 1985). The two negative anomalies displayed by cerium and europium are likely to be due to their variable oxidation states (Jarvis and Jarvis, 1985). The positive anomaly displayed by holmium is unexpected and may be caused by analytical error, as may the divergent pattern produced by lutetium; care must therefore be taken in the interpretation of these two elements.

The shale normalized patterns produced by the above samples are all similar and are, broadly speaking, horizontal. The sample from the marl seam has higher values than those from white chalk, confirming the observation that most of the REE are associated with clays. All the white chalk samples display a 'typical' limestone trend (Piper, 1974), with a slight Ce anomaly and a slight enrichment in the HREE relative to the LREE. The marl seam sample follows closely this trend but has a smaller Ce anomaly. Both Ce anomalies, and the slight differences in the white and marly chalk trends, are likely to be due to the presence of variable amounts of ocean derived carbonate and fish debris (see mineralogy). The anomalies displayed by Ho and Lu cannot be easily explained and, as noted above, may be due to analytical error.

This data shows that shale normalized REE patterns displayed by white and marly chalk are broadly similar and horizontal. The implication is that the clays present in both white and marly chalk are terrigenous in origin, and may well be derived from the same source. Little, if any, alteration of the clays has taken place whilst in the marine environment, and it is unlikely

that the clays are authigenic or directly derived from the weathering of igneous material. Additional REE data is presented in Section 6.3.3b.

6.3.3 Stratigraphic trends

a) Major and trace elements

Figure 6.8 shows a series of plots for the Middle and Upper Turonian marls from Sussex, concentrating on elements apparently associated with the clays.

The plot of aluminium can be used as an indicator as to the amount of clay present within the sediment. The most notable feature of the plot is the peak produced by Glynde Marl 1 and Southerham Marl 1. As it is unlikely that these two marls have undergone more post-depositional dissolution than those either above or below, the possibility exists that the higher values reflect sedimentological variations. From the discussion on the role of bioturbation (see Sedimentology), the higher percentages of clay may reflect either a decrease in the amount of bioturbation on the sea-floor or an increase in the rate of clay sedimentation. If the spike is ignored, the overall pattern demonstrates an upward decrease in the amount of clay present.

Potassium values, like aluminium, decrease upwards. A plot of K_2O/Al_2O_3 also decreases up section, although it is somewhat irregular in parts. Accepting that the major potassium bearing phase is illite (see above), the overall trend implies that the smectite/illite ratio increases up section. This may either be a reflection of increasing distance from source, or of differences in the speed of the transporting currents (Whitehouse *et al.* 1960, Jeans, 1968). The sharp drop in values coinciding with Glynde and Southerham Marl 1 is likely to be a reflection of increasing water depth and distance from source associated with the middle Turonian transgression (see Mineralogy).

The stratigraphic trend displayed by aluminium normalised potassium is sufficiently irregular to suggest that it may be possible to differentiate between elements associated with the smectite and elements associated with the illite, simply on the smoothness of the element/potassium curve. Elements mineralogically associated with the potassium (illite) should, when normalised against potassium, produce near-straight, horizontal lines, whilst

elements associated with smectite should produce a more irregular pattern, with values increasing up section.

Examination of the patterns produced by the various elements confirms the above proposition, as many of them show a very clear association with one of the clay minerals (see below)

Smectite associated elements: Si, Fe, Mg, Li, Na, Zn, Cu?, Zr?.

Illite associated elements: Ba, Sc, V, Ti?.

Non-clay associated elements: P, Y?, Ni?.

The above lists must however be treated with some caution, for example: although silica appears to be associated only with smectite, it is found in both clays in the approximate ratio of 2 silica: 1 aluminium, hence the horizontal SiO_2/Al_2O_3 simply reflects the chemical similarity of the two clays. Likewise, the gradual rise of the SiO_2/K_2O curve simply reflects the gradual decrease in the proportion of illite. Iron and magnesium are both important elements within smectite and the plots reflect this; importantly, MgO/Al_2O_3 climbs gradually up section, reflecting the relative increase in the proportion of smectite. Lithium, sodium and zinc show good 'smectitic' curves; copper and zirconium may be associated but the curves are more irregular, possibly indicating that the elements are present in other minerals.

The curves for barium and scandium indicate that these elements occur predominantly within illite, rather than smectite. In addition, V/K_2O whilst climbing slightly, is smoother than the plot of V/Al_2O_3 inferring that much of the vanadium is present in the illite. TiO_2/K_2O is slightly irregular but overall is sub-horizontal, implying that most of the titanium occurs within the illite.

The phosphorus plot is markedly different from that of aluminium, confirming that it is present in a separate phase (apatite - see above). Interestingly, although earlier evidence suggested that most yttrium was associated with the phosphate phase, Y/P_2O_5 displays a marked irregularity and overall is not as smooth as might be expected. In contrast, Y/Al_2O_3 whilst slightly irregular, is sub-horizontal in parts; the implication being that the Y may be present in both the phosphate and clay phases, with the latter containing the majority. Plots of Ni/Al_2O_3 and Ni/K_2O are both irregular, indicating that it may be present in other (authigenic?) phases.

b) Rare-earth elements

In addition to the results for a series of samples through New Pit Marl 2, most Middle and Upper Turonian marls and three insoluble residues from across Southerham Marl 1 have also been analysed (see Figures 6.9 - 6.11). Chondrite normalized trends are similar to those of New Pit Marl 2, all sloping from left to right and displaying negative Ce and Eu anomalies. The HREE trends of Middle Turonian marls vary slightly, possibly due to slight analytical variations.

The Middle Turonian shale normalized plots are near horizontal, with slight negative La, Ce, Eu and Lu anomalies. The Upper Turonian shale normalized plots show a similar pattern, but the middle rare earth elements (Pm to Ho, MREE) display a slight positive anomaly; a pattern which is amplified in the three insoluble residues from Southerham Marl 1 at Great Chesterford. Whilst slightly lower values for the LREE are likely to be due to the presence of small quantities of apatite and marine derived carbonate, the downward sloping trend displayed by the HREE is more difficult to explain. Because it is occurs in both whole-rock and insoluble residue samples, leaching of the clays during the carbonate dissolution process can be discounted. A possible solution has been proposed by Martin *et al.* (1976), Keasler and Loveland (1982) and Hoyle *et al.* (1984), as all have observed that the flocculation of organic matter colloids during estuarine mixing results in the preferential removal of the HREE from river water, which may in turn affect the proportion of REE adsorbed onto clays. Whilst the application of this observation to the patterns observed in the Chalk must be somewhat tentative, it is possible that a similar process took place when the terrigenous sediment entered the Chalk Sea. These difficulties should not however detract from the primary conclusion derived from the REE data so clearly illustrated by the insoluble residue trends of Southerham Marl 1 (Gt. Chesterford) *viz*, that the clays in white chalk and marly chalk have near-identical REE patterns indicating that the clay-grade material in both white and marly chalk is of terrigenous origin.

c) Comparison between white and marly chalks

The study of New Pit Marl 2 at Beachy Head showed that there was a slight difference in the clay mineral composition of white and marly chalks at that particular horizon. In order to determine if this is a characteristic feature of marls (see also Mineralogy), samples of both white and marly

chalk were collected from exposures between Puys and Belleville on the French coast. The fresh and wave-washed nature of this locality allows comparison between the two chalk types without the need to consider the effect of differential weathering. The two elements of particular interest to this study are potassium and aluminium as comparison of the aluminium normalized potassium results from white and marly chalks will indicate if there is a change in the smectite:illite ratio between the two. A table of the results obtained is presented below:

K_2O/Al_2O_3, French Coast

	Marly chalk	White chalk
Lewes	.103	*
Bridgewick 1	.110	.141
Caburn	.110	.179
Southerham 1	.077	*
Glynde 1 [Puys]	.112	.231
New Pit 2	.180	.209
New Pit 1	.190	

* = K_2O values below detection limit of ICP-AES

Although slightly incomplete, the results show that white chalks consistently have a higher proportion of illite (when compared to smectite) than adjacent marls, agreeing with the semi-quantitative X-ray diffraction data presented in Section 3.4.

6.4 CARBON AND OXYGEN ISOTOPE RESULTS

6.4.1 Previous work on chalks

a) Introduction

The chemically stable, low-magnesium calcite composition of chalks means that after deposition they tend to behave differently to most 'ordinary'

limestones. Hence, whilst limestones are greatly effected by early diagenetic effects (dissolution of unstable phases and cementation), chalks tend not to be (Bathurst, 1975). After burial, the low permeability of chalk tends to hinder the movement of large bodies of water through it (Scholle, 1977) other than along fractures, and hence diagenesis tends to proceed within a 'closed' system.

b) Carbon isotopes

Because of the relatively small amount of diagenetic alteration, many authors (for example Scholle, 1977; Scholle and Arthur, 1980) believe chalks to be reasonable recorders of oceanic surface water total dissolved carbon. Within the Upper Cretaceous, numerous analyses have been carried out, the most important 'find' produced to date being the marked increase in $\delta^{13}C$ near the Cenomanian - Turonian boundary (Oceanic Anoxic Event 2: OAE 2). This increase is well documented (de Graciansky *et al.*, 1986; Herbin *et al.*, 1986; Stein *et al.*, 1986; Schlanger *et al.*, 1987) and appears to occur on a world-wide basis. Above OAE 2, carbon isotope values decrease gradually, reaching a minimum near the Turonian - Coniacian boundary (Scholle and Arthur, 1980). In the Anglo-Paris Basin, OAE 2 occurs within and immediately above the Plenus Marls (Scholle and Arthur, 1980; Jarvis *et al.*, 1988a). Jarvis *et al.* believe OAE 2 was initiated by an upwelling event which caused a widespread increase in ocean-surface productivity. Actual values of $\delta^{13}C$ from the Plenus Marls at Dover give a maximum value of 4.75‰ (PDB) for the OAE (Jarvis *et al.*, 1988a) while chalks above have an average value of 2.44‰ (PDB).

c) Oxygen isotopes

Most early work on oxygen isotopes from chalks was concentrated towards interpreting diagenetic effects. For example, Scholle (1974) compared diagenetic features from chalk samples collected from different localities throughout the United Kingdom. He noted that "southern English chalks had received remarkably little diagenetic alteration" with the exception of "some loss of initial porosity through de-watering". Scholle reported that oxygen isotope results for southern England chalks were "not far from normal modern marine values" and had an average $\delta^{18}O$ value of -2.9‰ (PDB). Diagenetically modified samples from other areas had lighter $\delta^{18}O$ values (Northern Ireland average $\delta^{18}O$ was -5.6‰ (PDB), Yorkshire average $\delta^{18}O$

was -4.0‰ (PDB)). Scholle (1977) also agreed with Garrison and Kennedy's (1977) findings that much of the marly chalk was of diagenetic origin. He suggested that chemical compaction had caused the dissolution of calcium carbonate within clay rich units, the carbonate then being precipitated within adjacent clay-poor units.

Oxygen isotope data obtained by Jarvis *et al.* (1988a) across OAE 2 at Dover shows an increase in $\delta^{18}O$ values corresponding with the carbon excursion. This increase is enhanced by a relative decrease in $\delta^{18}O$ values both above and below it. Care must be taken in the interpretation of samples from above the Plenus Marls as they appear to have been collected from several different lithologies; including marls, flaser marls, exposed nodule beds and chalk containing numerous pebble intraclasts. Whilst not placing any significance on the stratigraphic variation of the $\delta^{18}O$ results, they noted that the more marly units exhibited higher $\delta^{18}O$ values than their adjacent chalks. They found it difficult to explain this variation but concluded that it was probably diagenetic.

6.4.2 Present work

a) Localities sampled and results

In an attempt to discover if there was any variation in carbon and oxygen isotopic values between marly chalk within marl bands and the white chalk above and below, a series of sub-samples were taken from the samples collected for geochemical analysis across New Pit Marl 2 at Beachy Head (NP2/BH). In addition to this, paired samples of white and marly chalk have been collected from other horizons and locations to see if the results from NP2/BH can be treated as typical for the Basin. NP2/BH was chosen because of its thick marl seam, and the absence in the white chalk above and below of nodular units formed during early diagenesis. For details of the experimental procedure see Appendix 3. The results are shown on Figure 6.12, plotted against a log of the section at Beachy Head. Results from other locations within the Basin are shown on Figure 6.13 and include a 'pair' of samples from NP2/BH. All results can also be found in Appendix 4.

b) Discussion of results

All results obtained in this study plot within, or very close to, the 'southern England' field of Scholle (1974). The carbon and oxygen results are discussed separately, in detail, below.

i) Carbon isotopes

The results from NP2/BH show that there is a slight upwards decrease in the $\delta^{13}C$ values from the bottom to the top of the section. There is however no variation in the values across the marl seam. The slight decrease seen directly above the seam may indicate the presence of a small quantity of isotopically lighter cement, as indicated by the carbonate geochemical analyses (Section 6.3.2d). The average value for the whole section is 2.15‰ (PDB) which is in good agreement with the results of Scholle (1974), and slightly lower than the mean value for the Lower Turonian obtained by Jarvis *et al.* (1988a) (2.83‰ PDB). Figure 6.13 shows that the NP2/BH results are very similar to those obtained from New Pit Marl 2 at Dover. Although the results for New Pit Marl 1 are slightly higher than those for New Pit Marl 2, they are both distinct from those higher in the succession (as are their respective white chalks). The Glynde Marls at Dover (Glynde II [Dover]) and Senneville have very similar values, although the result from the corresponding white chalk sample at Dover is slightly high. French samples of Southerham 1 and Caburn have slightly lower values, the white chalk below the Caburn Marl having the lowest value of all.

Overall, it appears that white and marly chalks both show a general decrease in $\delta^{13}C$ up-section, which is a reflection of the overall trend seen through the Turonian (as previously documented by Scholle and Arthur, 1980). It is caused by a combination of the positive $\delta^{13}C$ excursion found at the Cenomanian - Turonian boundary and the negative $\delta^{13}C$ excursion which reaches a minimum at the Turonian - Coniacian boundary.

ii) Oxygen isotopes

The results from NP2/BH show a marked variation in the oxygen isotope values between the marl seam and the chalk above and below. Within the marl seam the $\delta^{18}O$ values average -2.16‰ (PDB) with a standard deviation of 0.03 whilst the surrounding chalks have an average value of -3.14‰

(PDB) and a standard deviation of 0.23. Thus the marl seam is enriched in ^{18}O when compared to the chalk above and below. The $\delta^{18}O$ values for the white chalk are in good agreement with those published by Scholle (1974) for southern England although they are slightly more negative than the mean value for his nearest sampling point at Seaford Head (average -2.72‰).

Figure 6.13 shows that the trend displayed by NP2/BH is repeated throughout the Anglo-Paris Basin, marls consistently have a less negative $\delta^{18}O$ value than corresponding white chalks. The difference in $\delta^{18}O$ between a marl and its adjecent white chalk is variable; at Dover, the difference between New Pit Marl 1 and white chalk close to it is only 0.18‰ (PDB), whilst Southerham Marl 1 at Eletot is 1.26‰ heavier than its proximal white chalk.

The values of $\delta^{18}O$ discussed above may, unlike $\delta^{13}C$, be wholly or partly related to diagenetic effects, hence their interpretation is more difficult.

c) Sedimentological influences

On first examination of the results it was suspected that difference between white and marly chalks may in some way be related to the mineralogical composition of the sediment rather than actual fluctuations in carbonate $\delta^{18}O$ values. Pollution due to the leaching of loose hydroxyl groups from clays was prevented prior to analysis by cooling the released gas to below 0°C, a process which removes both water and hydroxyl groups (S. Hazeldine *in litt.*). Another possibility is the presence of small amounts of other carbonates such as siderite or dolomite in the marly chalks which, if only partially dissolved, will give rise to heavier $\delta^{18}O$ results. No such minerals have been reported from Turonian chalks from the centre of the Anglo-Paris Basin (although Quine (1988) describes dolomite from Haute Normandie) and none were discovered during this study (see Mineralogy). Hence it appears that the results do reflect true fluctuations in carbonate $\delta^{18}O$.

d) Diagenetic effects

Scholle (1977) argued that during burial diagenesis of chalks, after initial de-watering, chemical compaction caused by pressure solution is the most important process, with reprecipitation of the calcite taking place within

millimetres to metres of the source. Due to elevation of temperatures at depth, the precipitating calcite will be depleted in O^{18} relative to the surrounding chalk (see Bathurst, 1975). As the results from white chalks above and below NP2/BH are in good agreement with previously published values from southern England chalks which showed "remarkably little alteration" (Scholle, 1977), it would appear that large scale dissolution and reprecipitation has not taken place. Petrographic studies support this proposal (see Section 4.3) and, furthermore, the enrichment in ^{18}O within the marly chalk is the direct opposite of the pattern that would be expected if diagenetically precipitated calcite was present were present within it.

Directly above and to a lesser extent below the seam, $\delta^{18}O$ values are slightly more negative, probably indicating the presence of a small quantity of diagenetic cement (as demonstrated by the $\delta^{13}C$ results and the carbonate geochemistry; Section 6.3.2d). The source of the cement is likely to be the marl seam, as clay greatly assists in the dissolution process (see Section 2.8.3)

Evidence from other workers also implies that large scale dissolution of calcium carbonate did not produce marl seams. Coccoliths from within marl seams are generally better preserved than those from the surrounding chalk (J. Burnett, *pers. comm.*), Foraminifera within marl seams do show some evidence of dissolution (as argued by Ernst, 1978, 1982), but this is not widespread (P.N. Leary, *pers. comm.*; Leary and Wray, 1989) and is primarily restricted to planktonic groups.

Taking all the above into consideration, it appears that the major fluctuation in $\delta^{18}O$ occurring across the marl seam is unlikely to be related to diagenesis, although there is evidence above and below the seam that a small amount of dissolution has taken place. Primary factors must therefore be considered.

e) Primary effects

The oxygen isotopic composition of a carbonate precipitated from water depends principally on the isotopic composition of the water and its temperature (Epstein, *et al.* 1951, 1953). In the short term, isotopic variations within oceans are very small (Anderson and Arthur, 1983) due to the large mass of water, minor effects include continental runoff and variations in the amount of evaporation. A sudden increase in continental

runoff would cause $\delta^{18}O$ values to become more negative, the opposite of what is observed on entering a marl seam. Glaciation can have a marked effect, the storage of large quantities of isotopically light water as ice results in an increase in oceanic δO^{18} values. It is generally assumed that during the Late Cretaceous there was no polar ice (Hancock, 1975b; Frakes, 1979; Spicer and Parrish, 1990).

Not all organisms secrete calcite in equilibrium with the surrounding water (Anderson and Arthur, 1983), hence 'bulk rock' results may be affected if the relative proportions of the carbonate organisms change. Organisms which do not precipitate in isotopic equilibrium include species of coccoliths (Dudley *et al.*, 1986) and some benthic foraminifers. Examination of coccolith abundances across New Pit Marls 1 and 2 (Section 5.4) at Beachy Head shows that there are a few slight variations related to the presence of the marl seams, but these are always less than 5% of the total. Leary and Wray (1989) have found that the abundance of foraminifera groups varies across marl seams, a large proportion of it is however confined to planktonic forams which generally precipitate in equilibrium with sea water (Anderson and Arthur, 1983). Overall, although there are variations in the proportions of some of the calcareous organisms, it is unlikely that these are significant enough to produce the observed shift in the isotopic values.

If all the above evidence is taken into consideration it is difficult to put forward a simple explanation for the oxygen isotope variations. Clearly, some dissolution and reprecipitation of calcite has occurred but apparently only on a relatively small scale. A suggestion for a similar pattern observed across the clay-rich:clay-poor rhythms seen in the Lower Chalk (Ditchfield and Marshall, 1989), and for Cenomanian-Turonian sediments in Germany (Hilbrecht and Hoefs, 1986), is that the $\delta^{18}O$ fluctuations represent temperature variations within the water mass. Anderson and Arthur (1983) give the following palaeotemperature equation:

$$T°C=16.0-4.14(\delta_c-\delta_w)+0.13(\delta_c-\delta_w)^2$$

where $\delta_c=\delta^{18}O$ of the carbonate at 25°C (PDB) and $\delta_w=\delta^{18}O$ of the water relative to standard mean oceanic water (SMOW). Assuming a value for non-glacial Cretaceous sea water of -1‰ relative to SMOW (Lowenstam, 1964; Carson 1987), NP2/BH has a 'marly chalk' temperature of 21°C and a 'white chalk' temperature of 25.5°C. These values are unlikely to be exact due to biogenic fractionation of oxygen by various elements of the nannoflora but, as noted above, there is no major difference in the flora between

marly and white chalk, and therefore the results for the different chalks can be compared.

6.5 TOTAL ORGANIC CARBON

6.5.1 Introduction

A series of eighteen samples from above, below and within New Pit Marl 2 at Beechy Head were analysed using a Carlo Erba 1106 Elemental Analyser (at the School of Earth Sciences, Thames Polytechnic) in order to discover if there is any variation in total organic carbon (TOC) values across a marl seam. The results can be found in Appendix 4, and are plotted graphically on Figure 6.14.

6.5.2 Description and discussion of results

The results of this limited study show that there is no apparent variation in TOC on crossing the marl. There is a small, but unrelated peak approximately 40 cm above the marl seam. This data, coupled with the $\delta^{13}C$ results for the same marl, imply that marl seams were not formed through dissolution related to a lowering of the sea-bed pH due to the increased decomposition of organic matter, as has been suggested by Ernst (1982).

7. GEOCHEMICAL CORRELATION OF MIDDLE AND UPPER TURONIAN MARL BANDS

7.1 SUMMARY

By normalising to aluminium the geochemical results from a series of correlateable marl bands, collected from widely spaced localities within the Anglo-Paris Basin, it is possible to demonstrate that individual marls have a consistent composition which can be used to fingerprint them. Four elements are of particular value in the process: titanium, scandium, vanadium and yttrium.

Marls of unknown correlation were collected and analysed from within, above and below the Chalk Rock and Spurious Chalk Rock, and also from the Northern Province. Comparison of the Chalk Rock and Spurious Chalk Rock data with results obtained from the main part of the Basin shows that it is possible to assign 'basin' names to the previously uncorrelatable marls. This information can then be used to improve greatly our knowledge of the depositional history of these condensed units. Marls from the Northern Province cannot be correlated using this method, implying that their clays may be derived from a different source.

7.2 INTRODUCTION

The previous Chapter illustrated that it is possible to partition many of the elements into specific phases within marly and white chalks. It also demonstrated that the clay mineral composition and geochemistry of stratigraphically separate marl seams varied slightly. The aim of this Chapter is to see if the geochemical fluctuations observed in samples from Sussex also occur in samples from other parts of the Anglo-Paris Basin, and if so, to see if it is possible to geochemically 'fingerprint' individual marls. Samples have been collected from two additional areas: Kent (coastal exposures in the Dover area) and along the French coast (from the cliffs northeast of Puys).

7.3 ASSUMPTION

The primary assumption for much of the following work is that aluminium only occurs in an appreciable quantity within the clay minerals. Aluminium does also occur in other minerals found within marly chalks, notably glauconite and feldspar. Glauconite only occurs in trace amounts, and feldspar was not recorded in any of the samples examined (see Mineralogy).

7.4 COMPARISON OF STRATIGRAPHIC VARIATIONS IN COMPOSITION OF SAMPLES FROM KENT, SUSSEX AND THE FRENCH COAST.

7.4.1 Results

Plots of Al_2O_3 from the three localities show broadly the same pattern: one of decreasing clay content up-section (see Figure 7.1a), although results for some marls do differ (notably Glynde). Breaks in the lines signify absence of a marl at a particular locality (a Malling Street Marl does exist on the French coast but was not collected). Plots of K_2O and K_2O/Al_2O_3 from the three localities also show broadly similar patterns, supporting the hypothesis concerning fluctuations in clay mineral composition presented in Chapter 3 (see Figure 7.1b)

A series of graphs have been plotted to demonstrate similarities and differences for each of the elements associated with the clay fraction (see Figures7.1c -p). All the data has been normalized to aluminium so as to avoid discrepancies relating to the percentage of clay within the sediment.

Seven points are worthy of note:

1) Individual marls from at least two, and commonly all three localities, have very similar results for many of the elements.

2) Values for elements which show similarities often differ stratigraphically.

3) Individual elements are not always similar for all marls. For example: barium values from France are significantly higher than those from either Kent or Sussex in the Middle Turonian, but are similar in the Upper Turonian. Likewise, lithium values are very variable below the Caburn Marl, but above it they are very similar.

4) Results for some elements, such as nickel, are only similar in a small number of cases (in nickel's case: Glynde, Southerham 1 and Caburn).

5) Results for Glynde Marl 1 [Caburn, Puys; 2 Dover] are often different, the only exceptions being titanium and nickel. Occasionally it is possible to recognise a trend, for example: scandium values all show a sharp drop from New Pit Marl 2 to Glynde, and then a slight climb to Southerham Marl 1.

6) Titanium is the element showing greatest similarities between all three localities, this may be because it is present in relatively large concentrations.

7) Plots of Y/Al_2O_3 are often very similar, likewise plots of Y/P_2O_5 are also similar. It therefore seems likely that yttrium is present in both phases.

A summary of the similarities observed is presented in Figure 7.2, and the mean values and standard deviations for each element and marl are presented in Figure 7.3.

7.4.2 Discussion

The great similarity in aluminium normalized results from marls collected from widely spaced localities is significant and suggests that over a relatively wide area the clay mineral chemistry of a marl band remains surprisingly constant. Small variations within one marl from different localities may be due to one or more of the possibilities listed below:

1) The presence of authigenic phases or localised differences in the composition of the detrital mineral phase.

2) Distance from the source of the clays may cause slight compositional changes relating to their different settling rates, probably influenced in turn by the amount of current activity at the time of formation of the marl seam.

3) If the detrital minerals originate from more than one source, slight fluctuations in any of their inputs may influence the final composition.

4) Although every care was taken to ensure identical conditions for all analyses, samples were analysed randomly in a series of batches spread out over more than one year; hence inter-batch differences may have affected the final results.

5) Post-depositional leaching or weathering of the clays may have taken place, although little field evidence was found to support this proposition.

7.5 A METHOD FOR GEOCHEMICALLY FINGERPRINTING MARL BANDS

7.5.1 Method

Because separate marls have different average values for many elements, it is possible to correlate them geochemically. Although it may be possible to base such a correlation on the results of a single element, the risk of an anomalous result makes it more sensible to use a number of elements. Ideally, suitable elements should have near-identical values from each of the three localities, but between adjacent marls mean results should show significant differences.

Examination of the graphs and table of mean values shows that the Fe_2O_3/Al_2O_3 lines are sub-horizontal and therefore of little use, whilst the MgO/Al_2O_3 lines climb slowly and smoothly, making the differentiation of closely spaced marls exceedingly difficult. Other less than ideal elements such as Li, Zn, Ni and Zr have missing values or are only of use in isolated cases. Barium, in contrast, is a good element for use in fingerprinting marls from Kent and Sussex, but the higher French values make it less than ideal for widespread usage. K_2O/Al_2O_3 results may be of use, but some caution should be exercised due to its' poor detection limit when using ICP-AES. Four elements stand out as being the most suitable for geochemical 'fingerprinting', these are titanium, scandium, vanadium and yttrium: all have similar results for lithostratigraphically correlateable marls from the three localities, whilst at the same time having significantly different values for many adjacent marls. Their aluminium normalised results are illustrated graphically in Figures 7.4 and 7.5. Some care must be taken with yttrium because, as noted in the previous Chapter, at least some of it is likely to be contained within the phosphate phase. The apparent good correlation of Y/Al_2O_3 results between localities implies either yttrium is present in both phases or that the phosphate:clay ratio is constant between the three localities for correlateable marls and different between separate marls.

Although there is no predictable pattern up-sequence, certain marls are geochemically very distinctive, notably: the New Pit Marls, Southerham Marl 2, and Bridgewick Marl 2. The other marls in this part of the succession are more closely grouped, although they can still be distinguished from one another. Geochemical differences between marls appears to be related to the proportion of illite within the sediment. The stratigraphic plot of aluminium normalized potassium shows clearly that the distinctive marls mentioned above all have slightly higher K_2O/Al_2O_3 values than the marls above and below them, supporting the earlier proposal that the elements under examination are located primarily within the illite.

7.5.2 Correlation of the Glynde Marls

As previously noted (see Section 1.6.2 and Appendix 2), it is often possible to recognise a series of thin, often flaser, marls above the widely correlateable Glynde Marl *sensu* Mortimore and Pomerol (1987). Robinson (1986) discovered a total of six on Akers Steps; six can also be recognised on the French Coast near Puys, and at New Pit (near Lewes) a total of eight have been noted (see logs). Samples of Kent and French examples have been collected and analysed. The results obtained show that the aluminium normalised values of the correlateable marls (Puys 1, Dover 2) are quite distinct from the others, and that the letters' results are very variable (see Figures 7.6 and 7.7). The plotted data shows quite a broad scattering, making it difficult to propose suitable correlations between the two localities. More importantly, many of the higher marls have scandium and titanium values similar to those of the New Pit Marls, whilst yttrium and vanadium values are only slightly higher. Because of these difficulties, some caution must be exercised when proposing that an 'unknown' marl is the lateral equivalent of one of the New Pit Marls.

7.6 THE GEOCHEMICAL IDENTIFICATION OF UNKNOWN MARLS

7.6.1 Introduction

The ability to geochemically correlate individual marl bands from geographically widely spaced localities is a useful tool in confirming already established lithostratigraphic correlations. The true potential of the

method is in the correlation of unknown marl bands with those in the main part of the Anglo-Paris Basin. Two areas have been studied in detail in order to test this: 1) the Chalk Rock; 2) the Northern Province of Lincolnshire and Yorkshire.

7.6.2 The Chalk Rock and Spurious Chalk Rock

a) Introduction

The Chalk Rock Member is a condensed unit consisting of a number of mineralized and phosphatized hardgrounds which extend from Hertfordshire to Dorset. Bromley and Gale (1982) described in detail the internal stratigraphy and correlation of individual hardgrounds, but did not attempt to demonstrate how it correlated with the main part of the Anglo-Paris Basin. They split the Chalk Rock into three hardground suites, and noted the presence of three marls within it which they named the Fognam, Latimer and Reed Marls. The Fognam Marl occurs between the lower and middle hardground suites and is present over much of the area covered by the Chalk Rock. The Reed and Latimer marls occur within the middle suite, but are only developed in the expanded successions of Hertfordshire (see Figure 7.8).

b) Previous attempts at correlation

Although Bromley and Gale (1982) made no attempt to correlate the Chalk Rock with the main part of the Basin, several papers have attempted partial correlations: Mortimore (1977) argued that the Fognam Marl is the equivalent of Bridgewick Marl 1; Mortimore (1983, fig. 4a) proposed that at Mere and Charnage Down (Wiltshire) the Glynde Marl occurs beneath the Chalk Rock, Southerham, Caburn, Bridgewick and Lewes all being condensed within it. Mortimore and Pomerol (1987, fig. 6) proposed that, in the Faircross Borehole, a Southerham Marl (they did not specify which one) occurs below the Chalk Rock, the Caburn Marl within it, and the Bridgewick Marls just above it. They also suggested that in the Taplow Borehole a Southerham Marl occurs below the Chalk Rock, and the Caburn, Bridgewick and Lewes Marls are all condensed within it. Mortimore and Wood (1986) proposed that at Kensworth the Latimer Marl is equivalent to Southerham Marl 1, whilst the Reed Marl correlates with the Caburn Marl. Mortimore (1987, fig. 5) proposed that at Beggars Knoll one of the Southerham Marls occurs beneath the Chalk Rock, whilst at Fognam Farm

the Fognam Marl is the equivalent of the Caburn Marl (contradicting his 1977 paper).

'Basinal' correlations have also been made for marls above and below the Spurious Chalk Rock: Mortimore (1983) and Mortimore and Wood (1986, fig. 2.3) argued that on the Isle of Wight, a marl found a short distance above the Spurious Chalk Rock (the Black Band of Rowe, 1908) correlates with a Southerham Marl and the subsequent Grey Marl is equivalent to the Caburn Marl. Below the Spurious Chalk Rock they claimed to find Glynde Marl 1 [Caburn]. At Shillingstone Hill, Mortimore (1987) again proposed that the Glynde Marl occurs below the Spurious Chalk Rock, whilst a prominent marl a short distance above (tentatively called the Fognam Marl by Bromley and Gale, 1982) is the equivalent of a Southerham Marl.

c) Localities studied and results

In an attempt to clarify the correlation of the Chalk Rock and Spurious Chalk Rock with the rest of the Anglo-Paris Basin, marl seams from most of the above sections, and a temporary exposure near Burghclere, were collected and analysed using an identical method to that used above. Descriptions of the marls collected, detailed logs of the sections and the raw geochemical data can be found in Appendixes 2, 3 and 4. Their titanium, vanadium, scandium and yttrium resultshave been plotted on the same graphs as used for the main part of the Anglo-Paris Basin (Figures 7.9 and 7.10 for the Chalk Rock and Figures 7.11 and 7.12 for the Spurious Chalk Rock).

i) Burghclere

A temporary exposure created during road modifications south of Burghclere presented a superb section through much of the Middle and Upper Turonian, including the Chalk Rock. Four marls, three from below the Chalk Rock Member and one from within it, were collected and analysed (labelled on the graphs in ascending order 1-4). The lower three exhibited distinctive features, allowing them to be tentatively identified in the field as (in ascending order) New Pit Marls 1 and 2 and Glynde Marl 1 [Caburn]. The geochemical signatures obtained confirmed the field identifications (see graphs). The higher marl, predicted in the field to be a Southerham Marl, plots some distance away from the latter's field, and appears far more likely to be the lateral equivalent of the Caburn Marl. This proposition is

supported by the results of the Reed Marl from Kensworth (see below), which has near identical scandium and vanadium values. The overall implication of these results is that both Southerham Marls had been 'cut out' on hardgrounds.

ii) Fognam Farm

Named as the type locality of the Fognam Marl by Bromley and Gale (1982). Geochemical analysis of the Fognam Marl (labelled F on the graphs)produces a 'fingerprint' similar to that of Glynde Marl 1 [Caburn], although the vanadium value is a little high (see graphs). A thick marl occurring approximately 1 m below the Ogbourne Hardground was also sampled (labelled 1 on the graphs), it produces a signature similar to that of New Pit Marl 1, although once again the vanadium result is slightly high.

iii) Ewelme

A sample of the Fognam Marl (labelled 2 on the graphs) from this locality produces a fingerprint reminiscent of Glynde Marl 1 [Caburn], agreeing with the Fognam Farm result. A second, lower marl (labelled 1) was also sampled and gives a New Pit Marl 2 signature. The exact position of this marl below the Chalk Rock Member is difficult to ascertain due to poor exposure, but it seems unlikely that the distance between the two marls is more than 3.5 m.

iv) Beggars Knoll

Samples were collected from two marl seams occurring below the Chalk Rock. The results obtained imply that the higher marl (labelled 2 on the graphs) is the equivalent of New Pit Marl 2, and the lower (labelled 1) the equivalent of New Pit Marl 1 (although the yttrium result is higher than expected). It is unlikely that these marls are part of the Glynde Marl complex (see above) because the Ogbourne Hardground is present above them (Bromley and Gale, 1982), and at Fognam Farm the lateral equivalent of Glynde Marl 1 (the Fognam Marl) occurs above Ogbourne.

v) Kensworth

Samples of both the Latimer (labelled L on the graphs) and Reed (labelled R) arls have been collected and analysed. When plotted, the results agree favourably with the proposition made by Mortimore and Wood (1986), i.e. that Latimer is the lateral equivalent of Southerham Marl 1 and Reed is the equivalent of the Caburn Marl. Samples were also collected from marls further down the succession: the lowest marl collected (labelled 1) produces a fingerprint similar to Glynde Marl 1 [Caburn], marl 2 plots as a New Pit Marl, and marl 3 gives no clear signal. The most likely interpretation of this data is that marl 1 is Glynde Marl 1 [Caburn], and marls 2 and 3 are representatives of higher Glynde Marls.

vi) Shillingstone

Three marls were collected: one from below the Spurious Chalk Rock, and two from above it. Marl 1 (3.2 m below the hardground) produces a fingerprint which implies that it is one of the New Pit Marls, probably Marl 2. A problem with this interpretation is that lithologically the marl is very different from either of the New Pit Marls (see descriptions in Appendix 2). Taking this into consideration, an alternative interpretation is that it is a higher marl from within the Glynde Complex (see above). Further work to solve this problem was hampered by a 2-3 m high slope of scree which obscured the section below.

The two marls collected and analysed from above the hardground also produce results which are difficult to interpret. The lower of the two (labelled 2 on the graphs) produces values which imply that it probably Southerham Marl 1, although the vanadium value is markedly high. Marl 3 gives rise to a plot reminiscent of Southerham Marl 2, the only unfortunate exception being titanium which has a much lower value than might be expected. Overall, although not perfect, the geochemical results from these marls seem to imply that they are the lateral equivalents of the Southerham Marls.

vii) Isle of Wight

A series of four samples were collected across the Spurious Chalk Rock; two from below and the Black Band (labelled B on the graphs) and Grey Marl (labelled G) from above. The two marls from below (labelled in

ascending order 1 and 2) both give a signature reminiscent of the New Pit Marls, although it is difficult to differentiate further. As with the sample from below the Spurious Chalk Rock at Shillingstone, it is also possible that the marls are from the higher part of the Glynde Complex.

The Black Band also produces a confusing signature with both vanadium and yttrium values being higher than expected if it were Southerham Marl 1. The Grey Marl again has vanadium and yttrium values which are higher than usual for the Caburn Marl. Treating the marls as a pair, the consistently high results for two of the elements may be a reflection either of weathering (the Military Road section is heavily weathered) or of diagenetic influences, such as pore fluid movements, during the formation of the Isle of Wight Monocline. It is therefore tentatively concluded that they are the lateral equivalents of the Southerham 1 and Caburn Marls.

d) Summary

1) Most samples plot in or close to the fields produced by 'known' marls occurring in the main part of the Basin.

2) The three marls within and below the Chalk Rock as named by Bromley and Gale (1982) can be correlated with the main part of the Anglo-Paris Basin as follows:

Reed Marl = Caburn Marl.

Latimer Marl = Southerham Marl 1,

Fognam Marl = Glynde Marl 1 [Caburn]

3) The above correlation agrees with the published correlation of Kensworth (Mortimore and Wood, 1986) for both the Reed and Latimer Marls. It does not agree with the proposals made by Mortimore (1977, 1987) regarding the Fognam Marl which he believes to be of much younger age.

4) Care must be taken when attempting to interpret the marls occurring beneath the Chalk Rock because of the great similarity between the New Pit and higher Glynde Marls. At Ewelme and Fognam Farm the correlation of the lower marls with the New Pit Marls seems likely as they are lithologically similar and are overlain by the Fognam Marl (correlated with Glynde Marl 1). At Beggars Knoll the marls below the Chalk Rock are more likely to be the New Pit Marls because of Bromley and Gale's (1982)

proposal that the lowest hardground is Ogbourne; at Fognam Farm the latter is overlain by the Glynde Marls.

5) The results from the Isle of Wight and Shillingstone Hill partially agree with the proposals of Mortimore and Wood (1986) and Mortimore (1987) in that the marl above the Spurious Chalk Rock is probably Southerham Marl 1, and on the Isle of Wight it is succeeded by the Caburn Marl. Their proposal that the marl beneath the Spurious Chalk Rock correlates with Glynde Marl 1 [Caburn] is however doubtful, it seems more likely that it is either one of the higher Glynde Marls or that it is one of the New Pit Marls (see discussion above).

7.6.2 Conclusions regarding the Chalk Rock correlation

The geochemical fingerprinting of a series of marl bands from within, above and below the Chalk Rock and Spurious Chalk Rock provides a means of correlating these units with the main part of the Anglo-Paris Basin. The correlation of marls within the Chalk Rock with the expanded succession of Sussex is shown in Figures 7.13 and 7.14. The choice of hardground on which each of the marls is 'cut out' is based on data contained within Bromley and Gale (1982). These results support the proposal by Bromley and Gale (1982) that, in places, the Chalk Rock represents condensation of much of the Middle and Upper Turonian.

Not all samples analysed produced a reliable fingerprint, most notably those from beneath the Spurious Chalk Rock; further work, including the examination of additional localities, is required to fully resolve this problem.

In addition to the periods of non-deposition required for the formation of hardgrounds, there is also evidence of erosion of underlying sediments. At Fognam Farm, the lowest (Ogbourne) hardground appears to have 'cut out' New Pit Marl 2. In contrast, at Beggars Knoll the apparent correlative of New Pit Marl 2 is found some 3 metres below the Ogbourne Hardground. Accepting that both the hardground correlation of Bromley and Gale (1982) and the marl band correlation introduced in this work are correct, it must be concluded that at Fognam Farm erosion of underlying sediments occurred during the formation of the Ogbourne Hardground, removing at least 3 m of sediment including New Pit Marl 2.

7.6.3 Structural controls during the formation of the Chalk Rock and Spurious Chalk Rock

Subsidence during the Upper Cretaceous can be divided into two main forms: due to compaction of underlying sediments, and due to tectonic movements (Chadwick, 1985a and b). To the south of the London Platform much of the subsidence was due to compaction of underlying sediments, with relatively little tectonic subsidence. On the London Platform itself tectonic subsidence was much more rapid as the amount of compactable sediment below was much smaller.

Recently published data (Whittaker, 1985) has revealed much concerning the strata and structure underlying the Chalk. Included in this work are the positions of a large number of pre-Permian faults which acted as controls on Jurassic sedimentation (Arkell, 1933; Hallam, 1958). Cenomanian tectonic activity has been reported (Drummond, 1970), along a line extending from central Dorset to the Isle of Wight (the Mid Dorset Swell), a trend which corresponds to a concentration of pre-Permian faults (Figure 7.15). Another concentration of faults defines the southern edge of the London Platform, extending from Kent to the Mendip High.

The occurrence of the Spurious Chalk Rock in Dorset, underlain by a great thickness of Mesozoic sediment, is somewhat unexpected as one might have expected near continuous subsidence due to sediment compaction. The fact that some of the earliest hardgrounds are developed, whilst later ones are not, suggests that tectonic activity prevented subsidence and may even have caused slight uplift during the Middle Turonian, possibly along an axis corresponding with the Albian-Cenomanian Mid-Dorset Swell. The absence of later hardgrounds implies that subsidence commenced again during the upper Middle Turonian, at a rate faster than the late Turonian sea level fall. The presence of a 'complete' Chalk Rock across the northwestern end of the Wessex Basin, south of the London Platform, implies regional non-subsidence or uplift for much of the Middle and Upper Turonian, with similar depositional conditions to the London Platform. The thinning of the Chalk Rock in the Warminster-Mere region, noted by Bromley and Gale (1982), corresponds with a horst-like structure termed the Bruton High (Smith, 1985), implying that localised fault activity was also capable of influencing sedimentation.

The position of a basement fault to the north of Beggars Knoll (downthrowing to the south) may explain the preservation of New Pit Marl 2 beneath the Ogbourne Hardground, in contrast to the situation found at

Fognam Farm. A difference in the subsidence rate across the fault prior to, or during, the formation of the Chalk Rock may have either allowed a greater initial accumulation of sediment above New Pit Marl 2, or retarded scouring of already deposited material. Likewise, the slightly expanded succession at Burghclere occurs on the downthrow side of one of the faults defining the edge of the London Platform, .

The thinning of the Chalk Rock in the Chilterns (Bromley and Gale, 1982) cannot at this stage be explained using the idee of basement fault influence as none have been reported in this region. There are however significant changes in the age of the basement in this area (Whittaker, 1985; map 2), possibly implying some form of tectonic structure at depth.

7.6.4 The Northern Province

a) Introduction

Correlation within the Northern Province was demonstrated by Wood and Smith (1978), but linking it to the southern England succession has been hampered by the lack of palaentological agreement and subtle lithological differences. Nevertheless two attempts at correlation have been made by Wood *et al.* (1984) and Mortimore and Wood (1986) based on a combination of lithological, biostratigraphical amd geophysical evidence. A summary of their suggestions is presented on the left-hand side of Figure 7.18.

b) Results

A series of samples of all the named marls were collected and analysed; the results are plotted on Figures 7.16 and 7.17, and the raw data used can be found in Appendix 4.

Examination of the data shows that, as with southern England, correlateable marls have a similar clay mineral geochemistry. Unfortunately, the pattern produced by the Northern Province marls is somewhat different to that produced by those from those from southern England; nevertheless it is possible to propose a very tentative correlation.

The lowest marls examined have similar scandium and vanadium values to the New Pit Marls, although the yttrium and titanium values are somewhat high. Each of the Barton Marls plots discretely, Marls A,C and D plot close

to the bulk of the southern England marls, whilst Marl B plots closer to Southerham Marl 2. It is possible that Barton A is the lateral equivalent of Glynde 1 [Caburn], although both scandium and yttrium values are too high; Marl D also plots close to the Glynde field, but its' titanium values are too high. It seems very unlikely that Barton B is the equivalent of Southerham Marl 2. The plots produced by the Melton Ross Marl are broadly similar to those of Southerham Marl 1 (agreeing with Mortimore and Wood, 1986), although the yttrium result is slightly high and the vanadium result slightly low. The results of the Riby Marl plot close by those of Barton Marl B, and are similar to those of Southerham Marl 2. The two Deepdale Marls plot separately and could conceivably be the two Bridgewick Marls, although their vanadium results are lower than might be expected. The Beacon Hill Marl is similar to the Lewes Marl in many respects although with a slightly higher titanium value than usual. The Burnham/Welton boundary marl plots some distance from any of the known southern England marls. Likewise, a geochemical correlation using the North Ormsby Marl is unlikely, as it plots discretely some distance from the southern England marls. The Thornton Curtis Marl plots in, or very close to, Bridgewick Marl 1 causing somewhat of a dilemma, which is in part solved by the overlying Wootton and Ulceby Marls above which plot some distance from any of the Upper Turonian marls. Hence it seem seems likely that the similarity in composition of Thornton Curtis and Bridgewick 1 is coincidental.

c) Summary

An inter-basin correlation of this type is, by its very nature, somewhat tentative. Numerous assumptions have to be made, such as a single non-carbonate sediment source, a similar mineralogical composition when deposited, and similar diagenetic conditions. Additionally, chalks in the Northern Province are believed to have been deposited in much deeper water, under less variable conditions than those in southern England. A comparison of the potential geochemical correlation with that proposed by Mortimore and Wood is presented in Figure 7.18; unfortunately, with one exception, there is no clear cut agreement between the two. Accepting that all other available lithological, biostratigraphical and geophysical data tends to support the correlation of Mortimore and Wood (1986), it seems unlikely that the proposed geochemical correlation is correct. An alternative possibility is that the marls in the two provinces are unrelated to each

other, being merely a reflection of similar external factors, such as sea level fluctuations, which affected both basins simultaneously.

8.1 SUMMARY AND CONCLUSIONS

Marl bands are primary features of Turonian chalks in the Anglo-Paris Basin, which have subsequently been slightly modified by diagenetic processes such as compaction and pressure solution. They may contain a discrete, single bed of clay-rich chalk or a series of undulating, interwoven flasers (Section 2.4.4). They rest on a variety of chalk substrates. The frequent absence of lithified chalk beneath them enables one to infer that they are not simply formed as a result of a reduction or break in carbonate sedimentation, as is the case with clay-rich chalks found above omission surfaces (Section 2.7; Kennedy and Garrison, 1975).

The clay-rich chalk of marl seams is variously mixed by bioturbation with both the over- and underlying carbonate-rich chalk (Section 2.5.3). In some cases, the contrasting shades of the different materials depict individual burrows clearly. Marly chalk also infills burrows below the seam, and may be carried upwards by organisms entering the marl seam from above. Flaser marls are either formed through the complete bioturbational reworking of a thin seam of marly chalk, a process which results in the obliteration of the seam and the formation of a series of interwoven, thick flasers. Alternatively, they may be formed through alternating deposition of clay-rich sediment and white chalk, with subsequent bioturbation causing partial intermixing of the two sediment types (Section 2.6.4).

Visually, diagenesis has a more marked impact on flasers above and below the marl than on the seam itself. Flasers often show signs of compaction and carbonate dissolution, especially when they occur in nodular chalks (Section 2.9). Compaction has also affected clay-rich chalks overlying omission and erosion surfaces, primarily because the presence of cemented nodules cause non-uniform compaction of the sediment during diagenesis (Section 2.9.7).

The underlying sediments influence the nature of carbonate material contained within marls (Chapter 4). Marls resting on fine white chalks tend to contain fewer coarse fragments than the white chalk. Those overlying omission or erosion surfaces, and those deposited within a sequence of nodular chalks, are much coarser than those overlying white chalks and may indeed be coarser than the underlying sediment due to partial

dissolution of the fine carbonate fraction (as indicated by the presence of anastomising clay networks: Plate 17) or incorporation of a coarse, winnowed lag.

The mineralogy of the coarse fraction does not show consistant differences between marls and white chalks, and usually consists of a mixture of detrital quartz, authigenic pyrite and limonite, and biogenic carbonate apatite (Section 3.5). Smectite and illite are the main clay minerals present in white and marly chalks, kaolinite has only been found in some samples from Sussex (Section 3.4). Other minerals in the fine fraction include detrital quartz and biogenic carbonate apatite, and volcano-derived clinoptinolite occurs in all samples collected from Puys on the French coast. The smectite:illite ratios of white chalks adjacent to marl seams remain reasonably constant during the Turonian. Marly chalks, in contrast, display very variable ratios which always show a comparative enrichment in smectite. Stratigraphic variations in smectite:illite ratios of marly chalks through the Turonian are reasonably similar at all locations sampled, and can be interpreted as reflecting eustatic sea-level fluctuations documented by Hancock and Kauffman (1979) and Haq *et al.* (1988); during highstands the smectite:illite ratio is higher than during lowstands. This is a reflection of the differential settling rates of the clays (Section 3.4.4), which in turn is controlled by the distance that the clays are transported and the velocity of the transporting currents. Homogenisation through reworking, or a background aeolian input of illite, are possible reasons as to why clays in white chalks do not show a similar pattern.

Analysis of benthonic foraminifera species across a series of marls demonstrates that the formation of a marl had a marked effect on the epifauna, whilst leaving the infauna relatively unaffected (Section 5.2; Leary and Wray, 1989). The pattern displayed by planktonic foraminifera is less clear, probably due to their partial dissolution during diagenesis. The formation of a marl had little effect on either the nannoflora or dinoflagellates (Sections 5.3 and 5.4).

Major and trace element geochemical results support the proposal that marl seams are formed primarily by an increase in the proportion of clay minerals within the sediment (Section 6.3.2). Aluminium values show that, stratigraphically, the amount of clay in marl seams decreases upwards, although this may simply relate to the amount of bioturbation that the sediments have undergone (Section 6.3.3). Normalising all results to the aluminium value of the sample enables differentiation between clay- and

non-clay-associated elements, and also permits inter-sample comparison of clay-associated elements. Aluminium normalised potassium can be used as an indication of the ratio of illite to smectite, a stratigraphic plot follows closely the X-ray diffraction defined mineralogical pattern. Because potassium and aluminium do not co-vary, normalisation of clay-associated trace elements against both, from a number of samples, demonstrates in which of the two clay minerals each is found. Using this method it is apparent that barium, scandium, vanadium and (probably) titanium are contained within illite, whilst lithium, zinc, and (probably) copper and zirconium are contained within smectite.

Rare-earth element (REE) plots from New Pit Marl 2 (at Beachy Head) and white chalks above and below it show very similar patterns and, accepting that most REE are contained within the clays, the results demonstrate that the clays are detrital in origin and have undergone little or no alteration subsequent to their deposition (Section 6.3.2e). Data from other Turonian marls support these conclusions (Section 6.3.3b).

Calcium-normalised strontium and manganese ratios of the carbonate phase from samples taken above, below and within New Pit Marl 2 (Beachy Head) show that a small amount of carbonate dissolution may occur within a marl seam, with reprecipitation occuring in adjacent white chalks (Section 6.3.2d).

Oxygen isotope ratios support the above suggestion as $\delta^{18}O$ values are at their most negative directly above the seam, and also have a small negative deflection below (Section 6.4.2). More importantly, all marls examined have significantly higher $\delta^{18}O$ values than the white chalks above and below them (actual differences varying between 0.18‰ to 1.26‰ (PDB)). As diagenetic process have apparently had only a limited effect on marls and white chalks (Section 6.4.2d), the most likely explanation for the variation is that marl deposition was related to a basin-wide fall in water temperature. Calculations show that the fall may have been as much as 4.5°C in the case of New Pit Marl 2 at Beachy Head (Section 6.4.2e).

Carbon isotope values do not vary significantly across marl seams, and neither do total organic carbon (T.O.C.) results (Section 6.5). This data implies that marl formation is not related to increased deposition of organic material or the development of anoxic levels in the water column.

Basin-wide similarities in the geochemical composition of correlateable marl bands confirms the recently established lithostratigraphic schemes, and

demonstrates the remarkably consistant mineralogy of individual marl bands (Section 7.4). Geochemical fingerprinting of individual marls enables correlations to be made with marls in more condensed successions such as the Chalk Rock, demonstrating its complex history of formation (Section 7.6).

8.2 COMPARISON WITH SIMILAR HORIZONS

8.2.1 Marl bands in the Turonian of northwest Germany

A series of papers from various workers in Germany (including: Valeton, 1959, 1960; Dorn and Bräutigam, 1959; Seibertz and Vortisch, 1979) have shown that at least some of the marls in the German Chalk contain abundant volcanic debris. These marls (termed tuff layers) are usually between 2 and 10 cm in thickness, and consist of volcanic glass, clays (illite, kaolinite, illite/smectite and Fe-beidellite), feldspar, mica and heavy minerals. They are believed to be associated with sporadic volcanic events related to structural activity in Central Europe and southern Sweden (see Klingspor, 1976; Harrison *et al.* 1979), and can only be used for local correlation (Ernst *et al.*, 1983; Wood *et al.*, 1984). A similar, volcanic origin has ben proposed for marls in the English Chalk (Pacey, 1984; Robinson, 1984; Leary and Wray, 1989).

Also present in the German Chalk is another suite of clay-rich horizons termed marl layers. In the field these appear very different to the tuff layers (C.J. Wood *pers. comm.*) and, importantly, it is these layers which may be of use in the correlation between Germany and England (Wood *et al.*, 1984). From this it seems likely that German marl layers may have been caused by a similar process to that which formed marls in the Anglo-Paris Basin, although the source of the clays may differ.

8.2.2 The Plenus Marls.

The meticulous work of Jefferies (1961, 1963) demonstrated that within the late Cenomanian Plenus Marl, beds 1-8 could be recognised across most of the Anglo-Paris Basin. Erosion surfaces underlie the more marly beds (1, 2 and 4), and are particularly prominent under Beds 1 and 4. Between Beds 4 and 6 a significant change in the fauna occurs, with the incoming of

Actinocamax plenus (Blainville)and *Oxytoma seminudum* (Dames), both of which have been interpreted as reflecting the incursion of cooler, Boreal waters, since both species are common on the Russian Platform.

The discovery of a world-wide oceanic anoxic event at this level (Schlanger and Jenkyns, 1976) has resulted in a series of detailed papers examining aspects of the Cenomanian-Turonian boundary across Europe (Jenkyns, 1980; Pomerol, 1983; Hart, 1985; Herbin *et al.*, 1986; Hilbrecht and Hoefs, 1986; Kuhnt *et al.*, 1986; Jarvis *et al.*, 1988a; Jarvis *et al.*, 1988b).

The Plenus Marls have many features in common with marls higher in the Turonian: clay rich layers are not underlain by cemented chalks, clay-rich layers overlying erosion surfaces tend to be coarser (Jarvis *et al.*, 1988a), their formation seems to be associated with a regression, and oxygen isotope values can be interpreted as reflecting lower sea water temperatures (Hilbrecht and Hoefs, 1986). There are however marked differences such as the association with a $\delta^{13}C$ excursion, and the multi-bedded nature of the unit.

Jefferies (1963) proposed that the Plenus Marls were formed as a result of river downcutting and erosion, associated with a fall in sea-level, which consequently caused an increase in the amount of non-carbonate sediment introduced into the Basin. There is however good evidence that the climate of emergent land masses in northwest Europe was arid and non-seasonal (Hancock, 1975b) which would tend to negate river erosion and transportation as an important process.

Jarvis *et al.* (1988a) proposed that the Plenus Marls were formed during a transgression, the increased percentage of non-carbonates being derived from recently inundated land areas and from winnowing of the fine calcitic fraction during periods of higher current activity. Evidence for a transgression at the base of the Plenus Marls is somewhat lacking, especially when it is remembered that at many of the localities documented by Jefferies (1963), which are believed to be at the margins of the Basin (including Beer, north Norfolk, and the western part of the Paris Basin), the Plenus Marls are either condensed or completely absent. Microfaunal patterns are believed to have been controlled by the anoxic event (Jarvis *et al.*, 1988a), although it appears that bioturbating organisms were rather less affected (A.S. Gale, *pers. comm*). The effect of the influx of clay on the biota is somewhat ignored by Jarvis *et al.*, despite its apparently

marked effect on fauna contained within marls higher in the Turonian (Leary and Wray, 1989).

8.3 THE ORIGIN OF MARL BANDS

8.3.1 Source of the clays

The high sea-levels of the Upper Cretaceous resulted in a great reduction in the amount of land available to supply clastic sediments. Our knowledge has been further reduced by Tertiary uplift, which has resulted in the erosion of many marginal deposits.

Of the marginal facies which are still preserved around the edges of the Anglo-Paris Basin (see Section 1.8), only one contains a high enough percentage of clay to make it a potential source of the non-carbonate material. A large area of clastic-rich marginal deposits occurs in northern France and Belgium, around the borders of the Ardennes (Barrois, 1878; Cornet, 1919; Waterlot, 1963; Celet, 1969). It consists of greenish-grey marls, and glauconite-rich units. Godfriaux and Robaszynski (1969) described Lower and Middle Turonian marly sediments from the Mons Basin which contain 10-15% kaolinite, 10-15% smectite and 10-30% illite. Accepting that transportation of clays will result in their relative proportions changing due to differential settling (especially close to source, see Section 3.4.4b), this region provides a likely source for the clays contained within marls. Clays contained within white chalks may also have originated from this region, but their pre-burial history is probably more complex (see Section 3.4.4c).

8.3.2 Hydrological controls on marl formation

With the exception of the Lower Turonian, all marls found in Upper Cretaceous chalks have been deposited during eustatic low-stands of sea level (Section 2.4.2).

Their occurrence as discrete beds suggests that the processes responsible for their formation commenced suddenly and only lasted for a short period of time, possibly indicating that regressions in the Upper Cretaceous

occurred in a series of sharp steps rather than gradually over a long period of time.

Evidence from oxygen isotope studies indicates that marl formation is associated with the presence of cooler water (Section 6.4.2e). The sharpness of the $\delta^{18}O$ change suggests that it is unlikely to be caused by a general cooling of water within the Basin (which would give rise to a smooth, gentle change in $\delta^{18}O$), and thus it probably reflects a sudden influx of cooler water into the Basin. As it is doubtful that cool Atlantic bottom water would be capable of entering the Basin during low-stands, the most likely source of the water is the North Sea. This proposal is supported by existance of a Boreal fauna within Beds 4-6 of the Plenus Marls (Jefferies, 1961; Section 8.2.2).

8.3.3 Erosion, transportation and deposition of the clays

Ernst *et al's.* (1983, Fig. 7) model of current patterns in the North Sea proposed that the dominant trend was north-south, with currents turning westwards as they came into contact with the Mid-European High (see Figure 8.1). If falls in sea-level occurred more quickly within the Anglo-Paris Basin than in the North Sea, or if the North Sea was not directly linked to the Atlantic, cooler northern water may have entered the Anglo-Paris Basin across the London Brabant Massif, passing close to marginal sediments on the borders of the Ardennes. Shallowing related to the presence of the Massif is likely to have caused an increase in current velocities, enabling erosion of clay-rich sediments to take place. Falling sea-level may have aided the process of erosion by causing pore-water overpressuring, resulting in sediment instability similar to that described by Hilbrecht (1989). The increase in current speeds caused by the regression probably prevented quick settling of the clays after they had entered the Anglo-Paris Basin, whilst the higher density of the cooler water entering the Basin is likely to have caused it to sink, permitting relatively quick deposition of the clay-rich sediment when current speed finally slowed. A combination of these processes resulted in thin but laterally continuous beds.

8.3.4 The formation of marls in the Lower Turonian

Marls in the Lower Turonian were apparently deposited during a transgression. It seems likely that many of the minor and laterally discontinuous marls which were deposited during this period may simply have been formed as a result of the encroachment of the sea onto the Ardennes and other areas. However it is not inconceivable that the transgression was interspersed with short periods of still-stand or even regression, especially in its later stages, which may have permitted the above processes to occur.

ACKNOWLEDGEMENTS

I owe much thanks to Prof. Jake Hancock, Dr. Andy Gale and Dr. Pete Gutteridge for their supervision and guidance during the course of this work. Andy Gale deserves special thanks for his encouragement and assistance in the field, and his extra-curricular evening classes in intoxication and gluttony.

At various stages during the project I have greatly benefitted from discussions with Richard Bromley, Greg Carson, Peter Ditchfield, Malcolm Hart, Dave Horne, Ian Jarvis, Chris Jeans, Paul Leary, Rory Mortimore, Chris Paul, Stuart Pratt, Nick Robinson, Ian Slipper, Bob Stokes, Max Williams and Chris Wood. Many thanks to Paul Leary, Jackie Burnett and Meriel Fitzpatrick for supplying the micropalaeontological data, and to Peter Ditchfield and the Stable Isotope Laboratory, Department of Earth Sciences, Liverpool University for supplying the stable isotope data.

Chris Wood is also thanked for his guided tour of the Chalk of Yorkshire and Lincolnshire. Max Williams and Phil Hood provided much-needed assistance in the field on numerous occasions, and Jenny Bennett kindly provided accomodation during my studies of the Sussex chalk.

Technical assistance from Barry Saunderson, Ian Slipper, Pat Brown, Hilary Foxwell, Bill Ralph, Rose Gent and Nick Dobson, along with all the other members of staff at the Department of Geology, City of London Polytechnic / School of Earth Sciences, Thames Polytechnic is gratefully acknowledged. The patience of Albert Hodgkinson and his schoolkeepers was appreciated on numerous occasions during the course of this work.

Andy Gale, Greg Carson and Jeremy Young ridiculed earlier drafts of the thesis.

My mother, father, sister and brother-in-law continually expressed their interest and support over the years, for which I will always be grateful.

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VOLUME 2

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Figure 1.1

AREA OF CONFIDENT MARL BAND CORRELATION WITHIN THE ANGLO-PARIS BASIN.

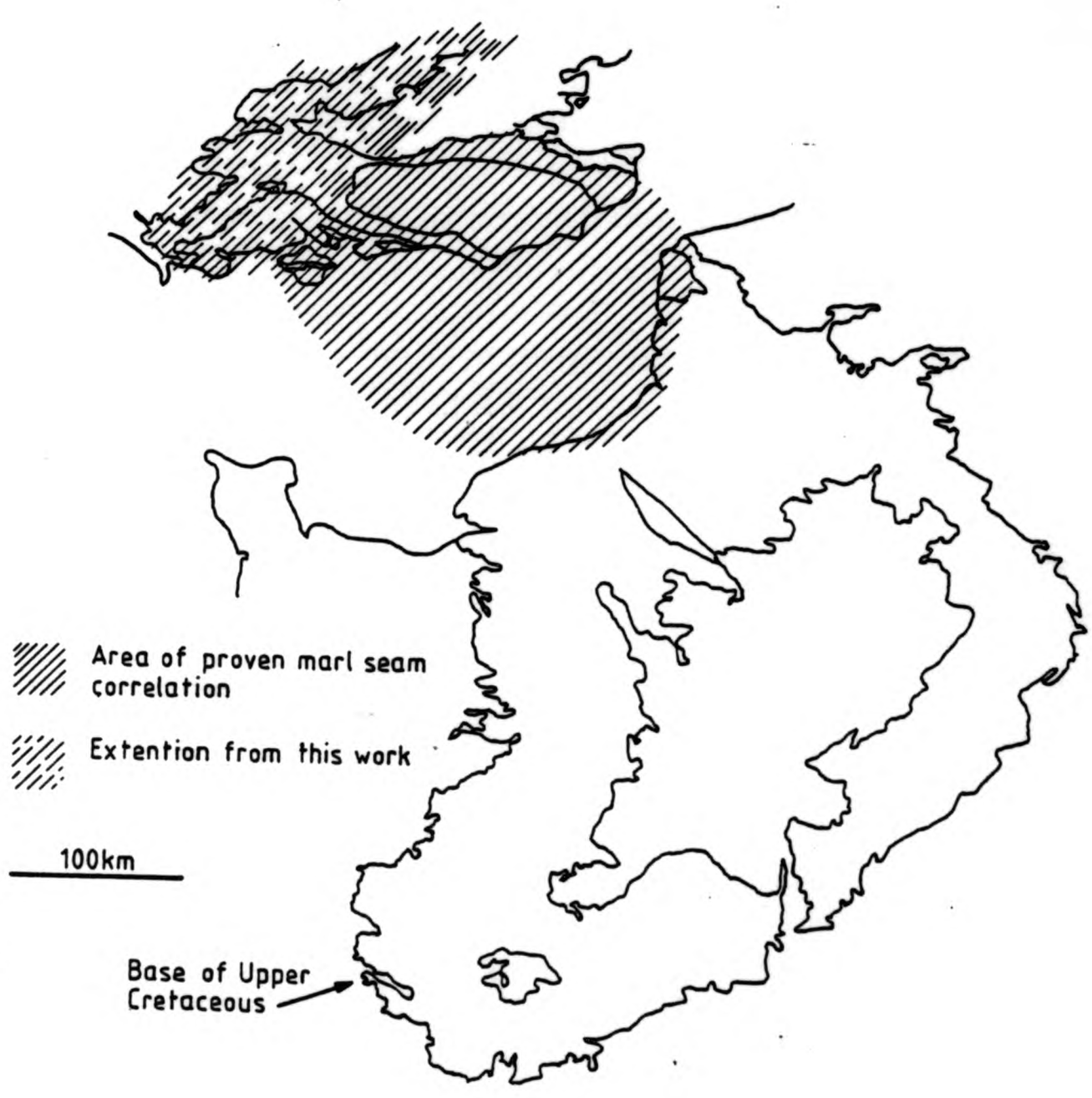


Figure 1.2

MAP OF THE PRINCIPAL LOCALITIES EXAMINED.

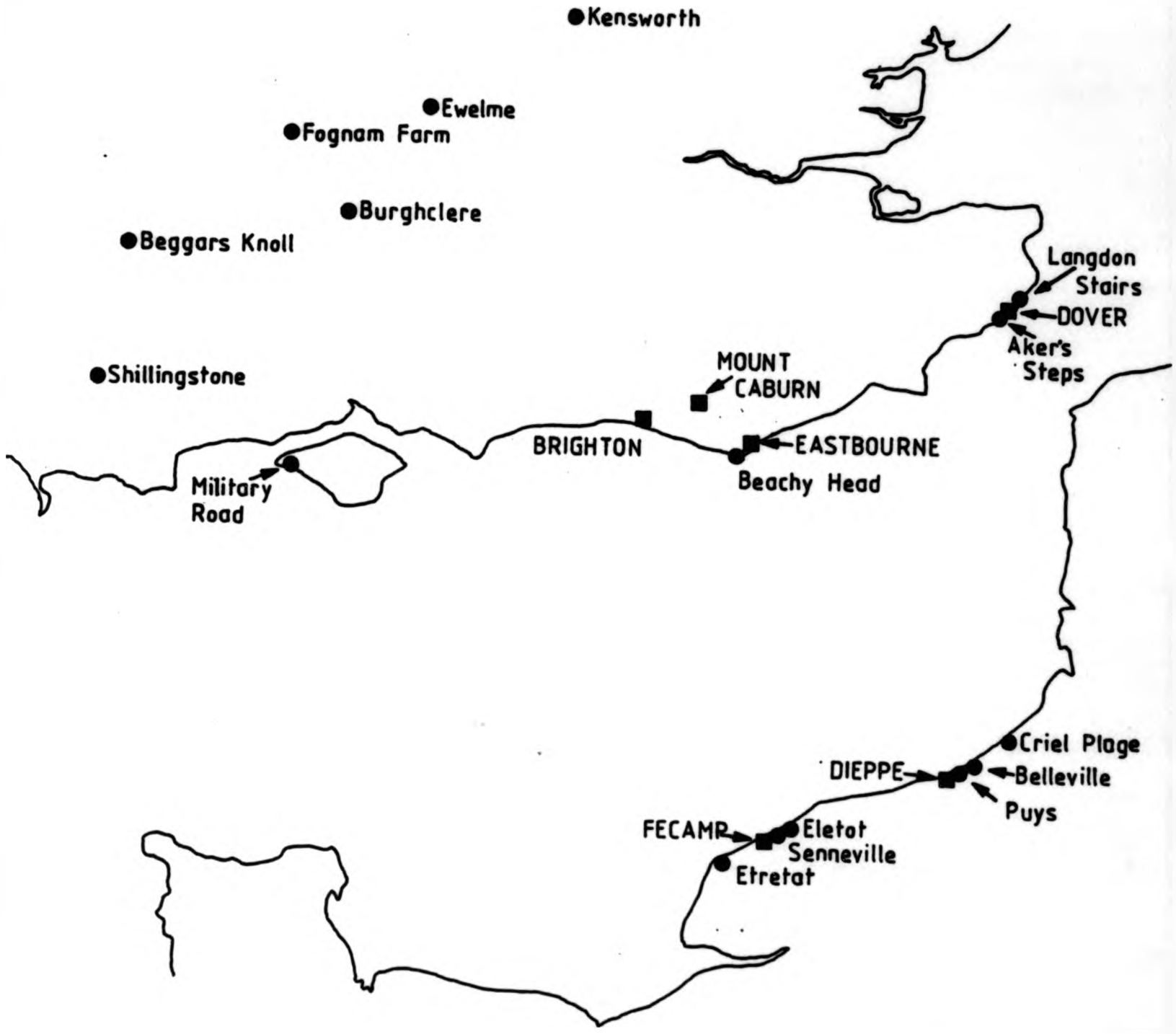
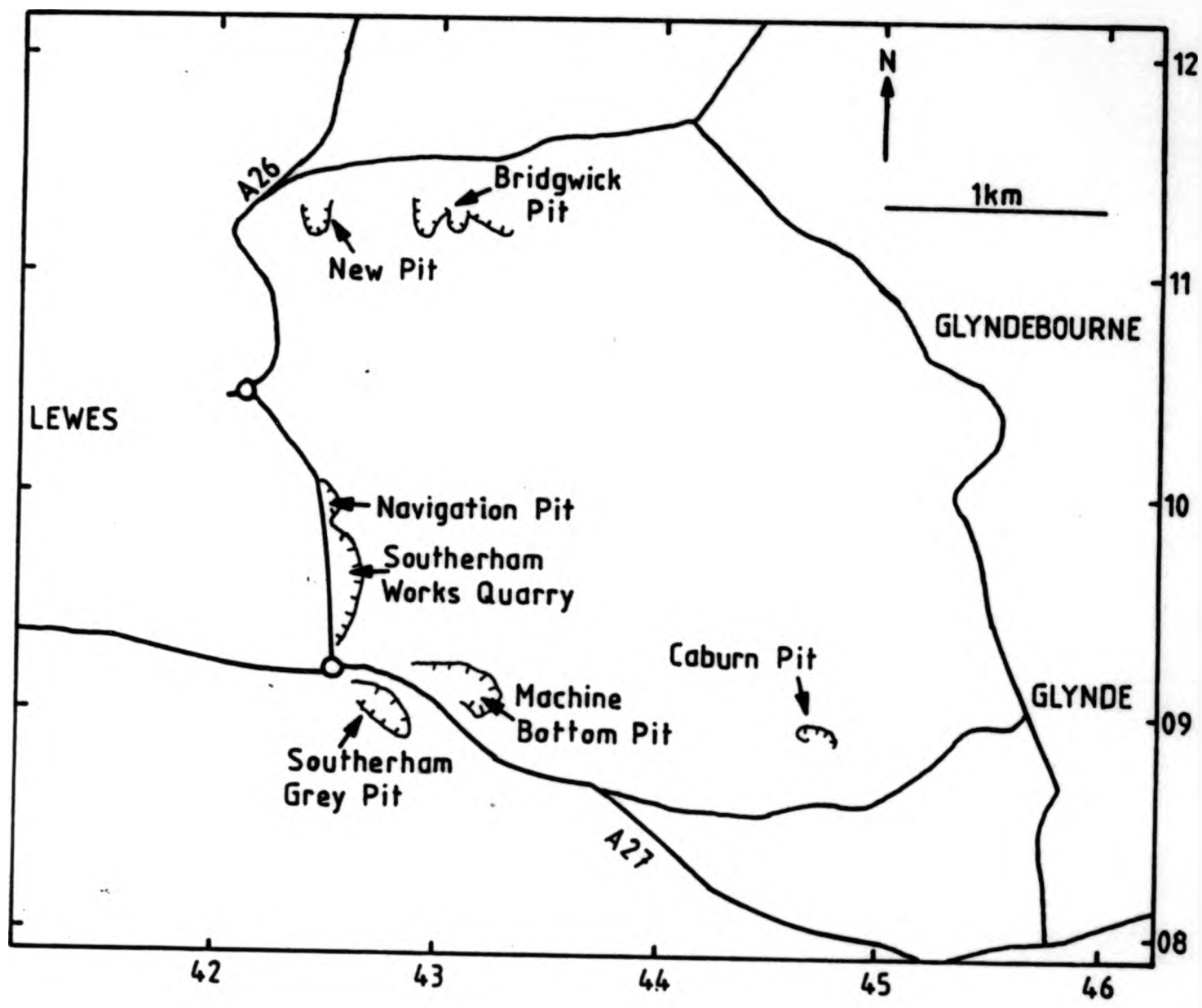


Figure 1.3

DETAILED MAP OF THE MOUNT CABURN PITS. SUSSEX.



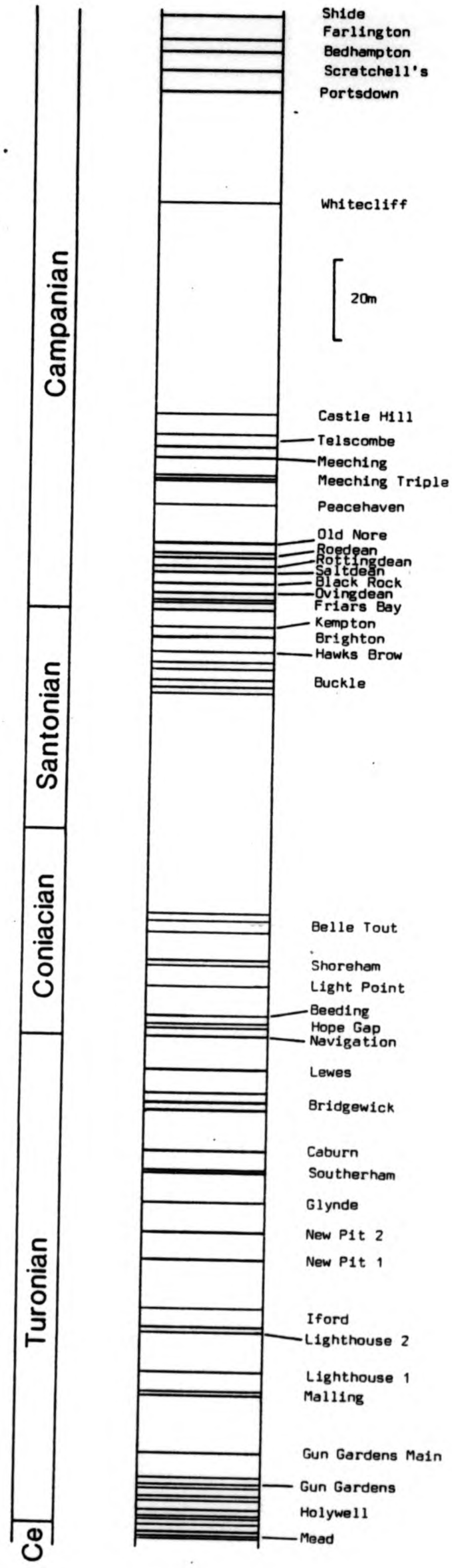


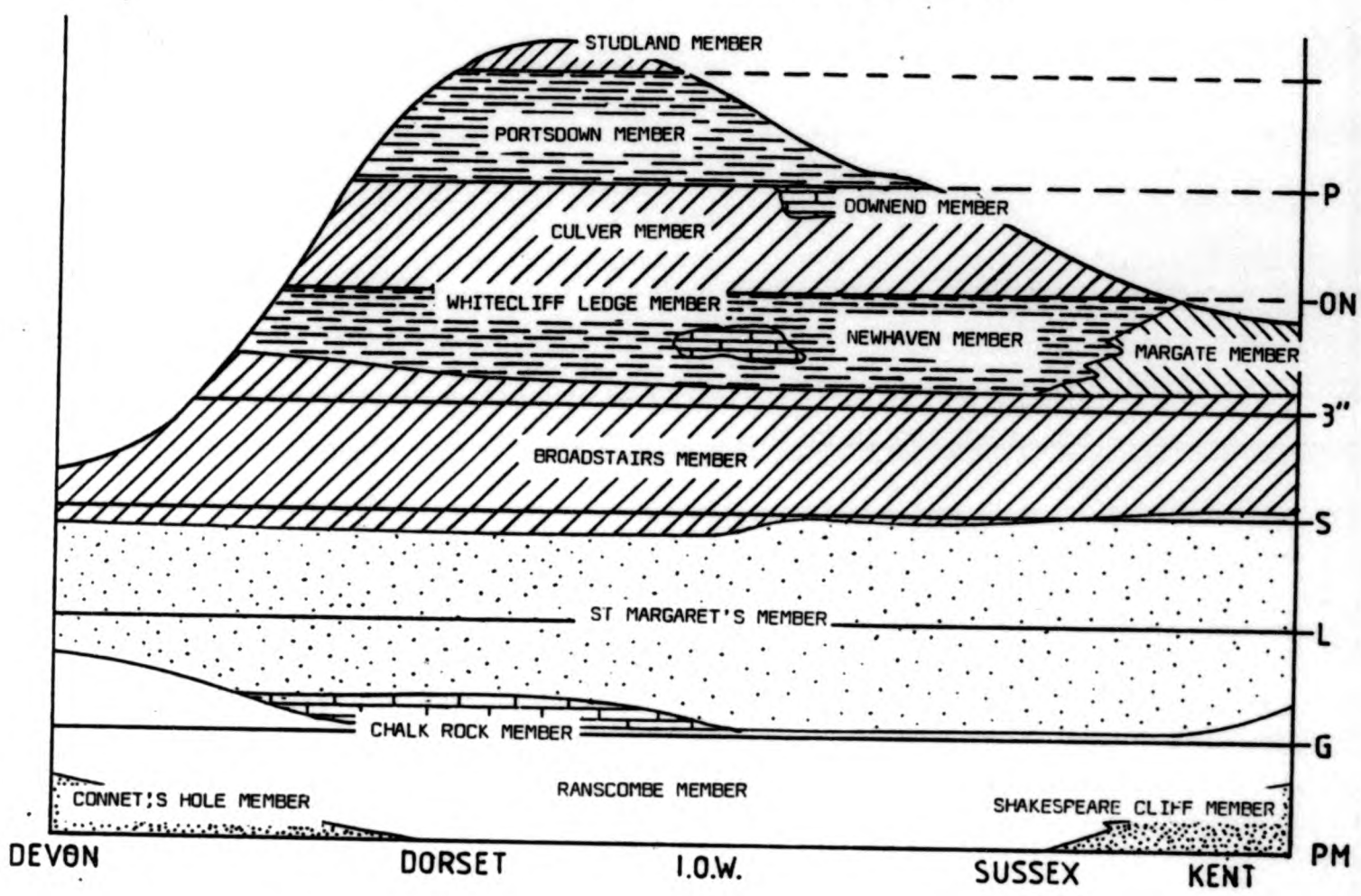
Figure 1.4

SIMPLIFIED LOG SHOWING THE STRATIGRAPHIC DISTRIBUTION OF MARLS IN THE ANGLO-PARIS BASIN (nomenclature from Mortimore 1986a).

Figure 1.5

MIDDLE AND UPPER CHALK LITHOSTRATIGRAPHIC MEMBERS

(after Gale, Wood and Bromley, 1987).



Chalk containing numerous flaser marls and few flints.

Intensely nodular calcarenitic chalk.

Chalkstones and intensely nodular chalks.

Flinty chalk containing beds of nodular chalk.

Marl-free chalk containing numerous beds of flints.

Marly chalk containing numerous flints.

Marl-free chalk with few flints.

Figure 1.6

THE RELATIONSHIP OF MARL BAND NOMENCLATURE BETWEEN THE LITHOSTRATIGRAPHIC SCHEMES OF MORTIMORE (1986a) AND ROBINSON (1986a)

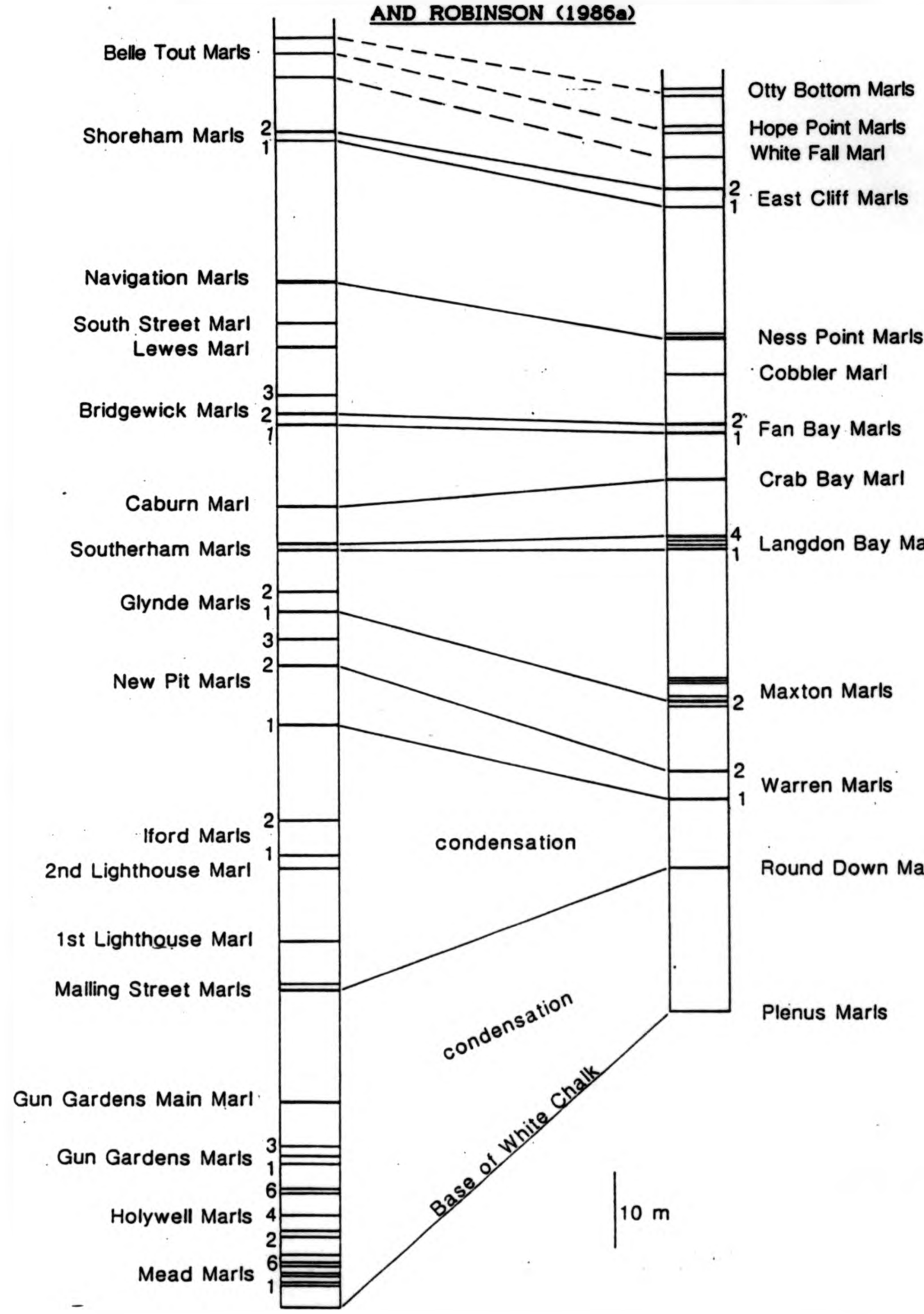
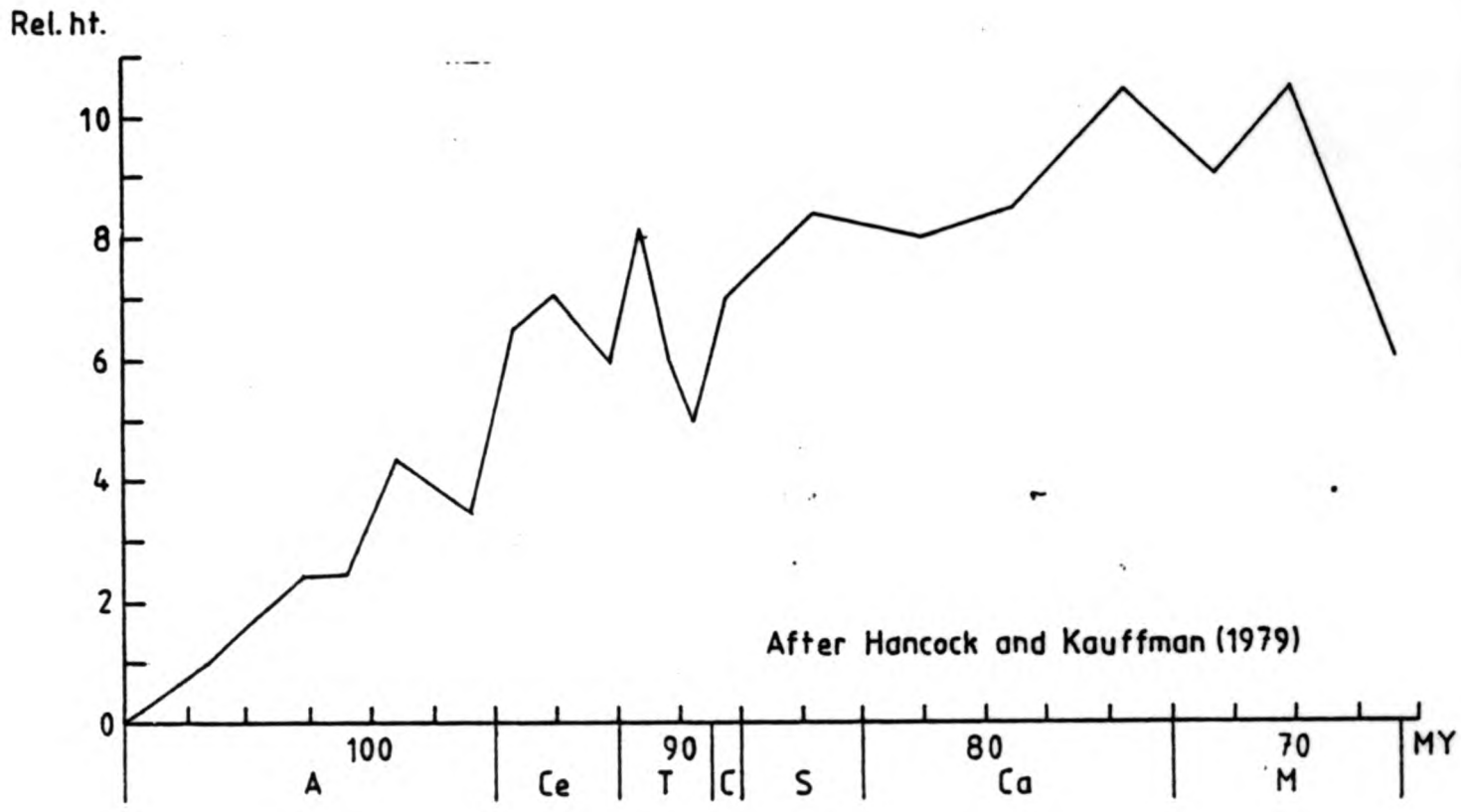


Figure 1.7

SEA-LEVEL FLUCTUATIONS IN THE UPPER CRETACEOUS ACCORDING TO HANCOCK AND KAUFFMAN (1979) AND HAQ *ET AL.* (1988).



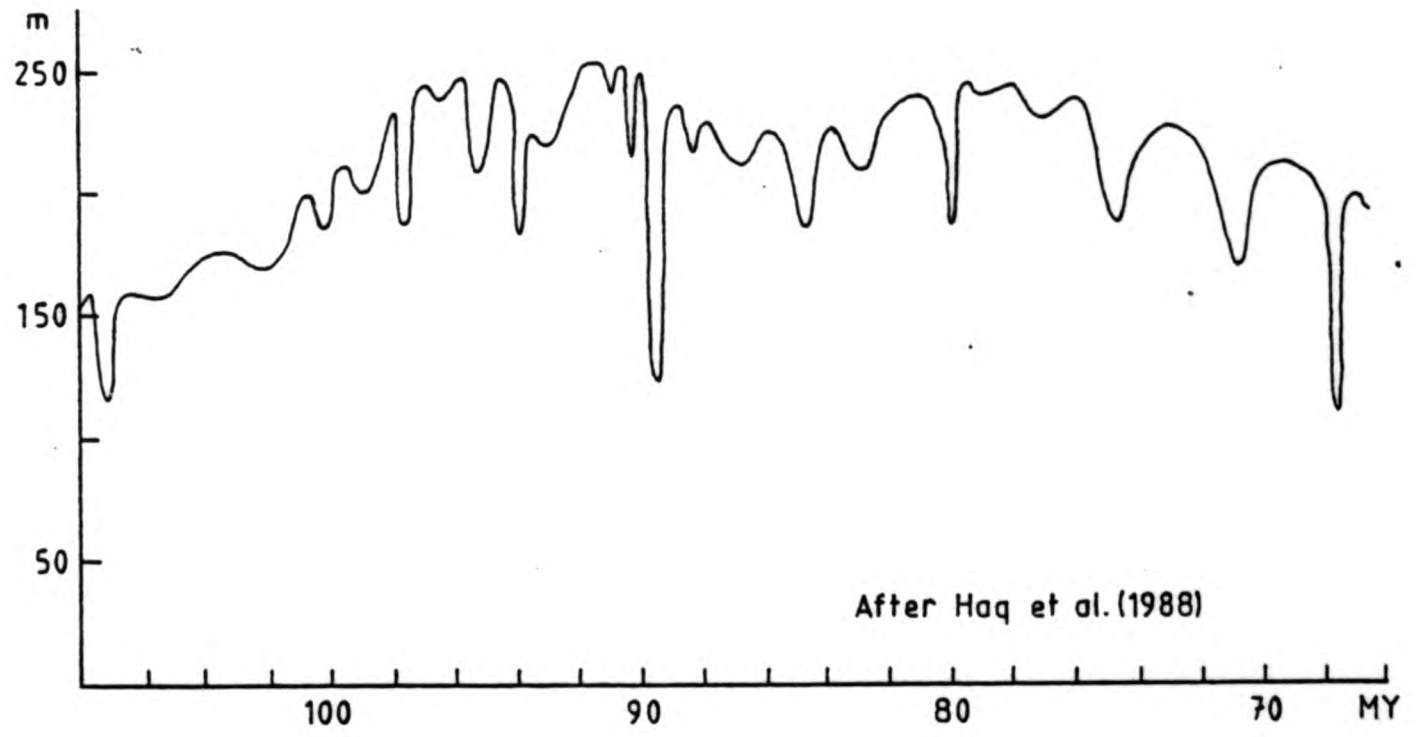


Figure 1.8

TURONIAN PALAEOGEOGRAPHY OF NORTHWEST EUROPE

(after Hancock, 1984 and Ziegler, 1982).

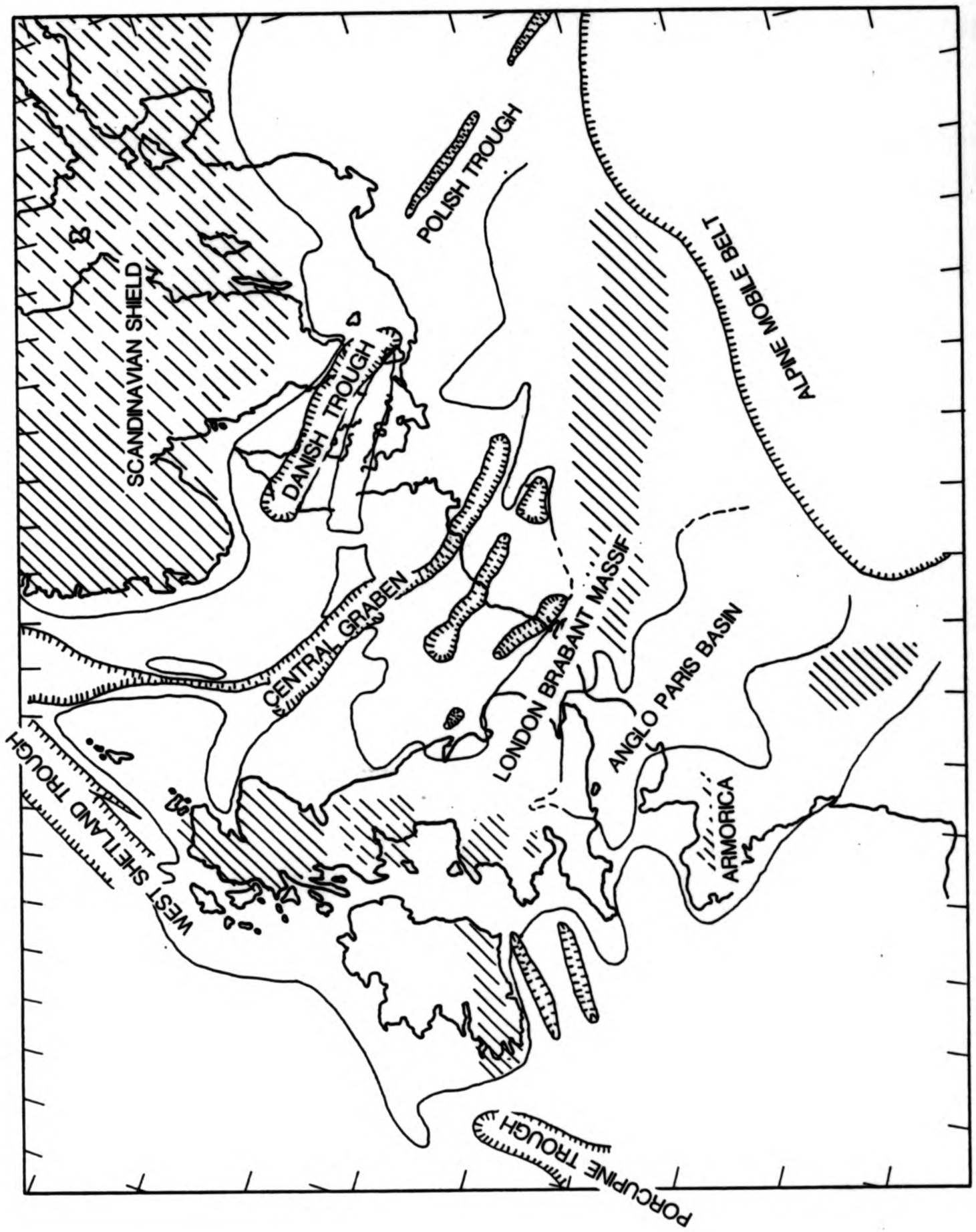


Figure 2.1

TRACE FOSSIL ASSOCIATIONS AND TIERING IN UPPER CRETACEOUS CHALKS (after Bromley and Ekdale, 1986a).

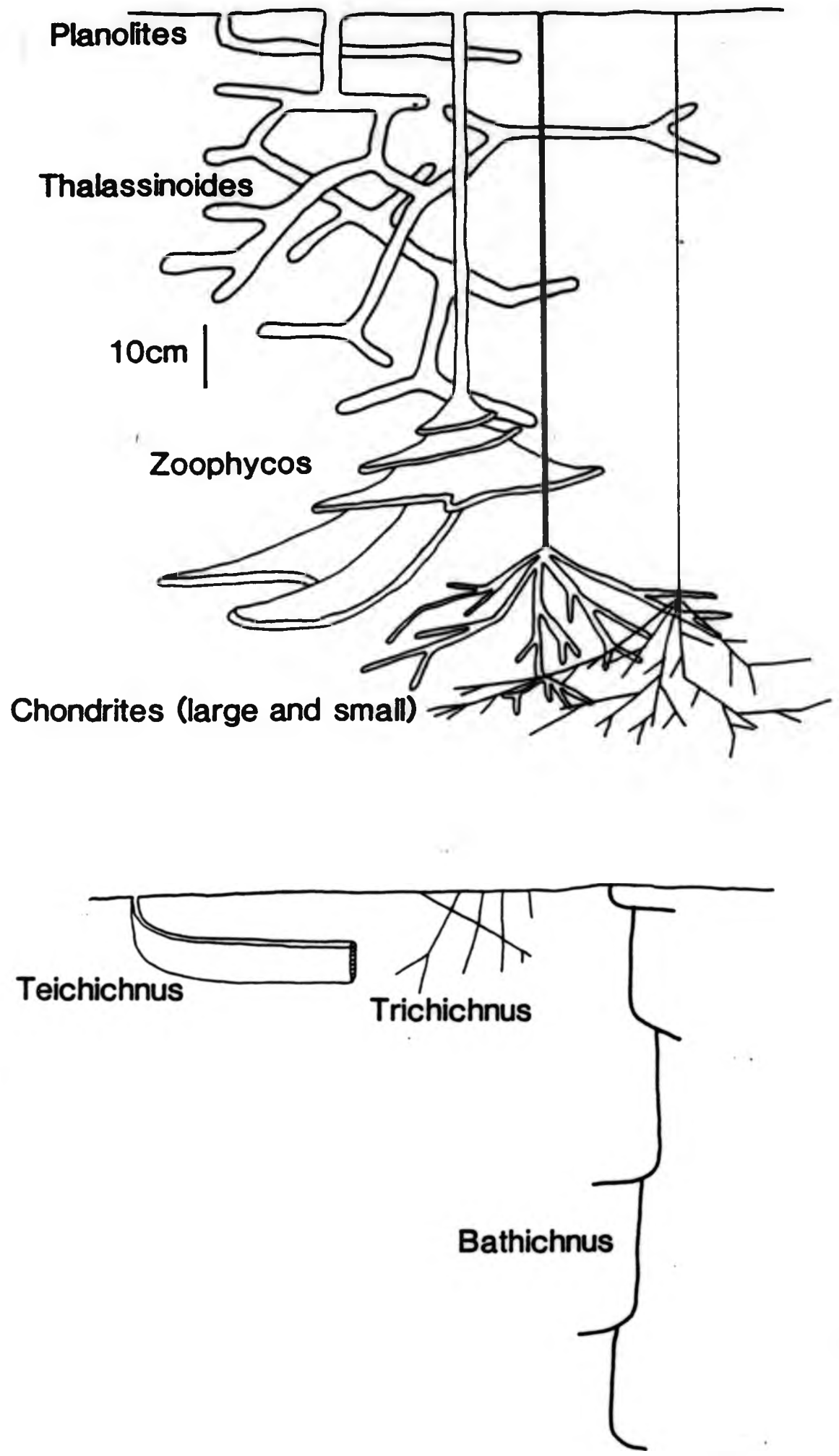


Figure 2.2

NEAR-SURFACE BURROW PRESERVATION IN RECENT PELAGIC SEDIMENTS

(after Berger *et al.* 1979).

0 cm	
MIXED LAYER (no record preserved)	Uniform colour. Soft, intensely burrowed by small organisms. Abundant tiny vertical burrows. Open shafts.
5-8 cm	
MIXED LAYER TRANSITION (partial record)	Similar to above but firmer, with much fewer open shafts. Commonly light coloured blebs floating in Mixed Layer matrix.
10-13 cm	
TRANSITION ZONE (maximum record)	Maximum colour contrast. Firm sediment. No living organisms seen. Intensely burrowed. Burrows are relatively large. Several generations of burrows with large range of preservation. Shallow cores have vertical burrows.
20-35 cm	
HISTORICAL LAYER (fading record)	Fading colour contrasts. Stiff sediment. Burrows and associated reduction haloes grade into 'mottles'. Burrow preservation deteriorates. Vertical burrows rare, even in shallow cores.

After Berger et al. 1979.

Figure 2.3

PLOT OF MARL BAND INTENSITY AND SEA-LEVEL FLUCTUATION FOR THE UPPER CRETACEOUS.

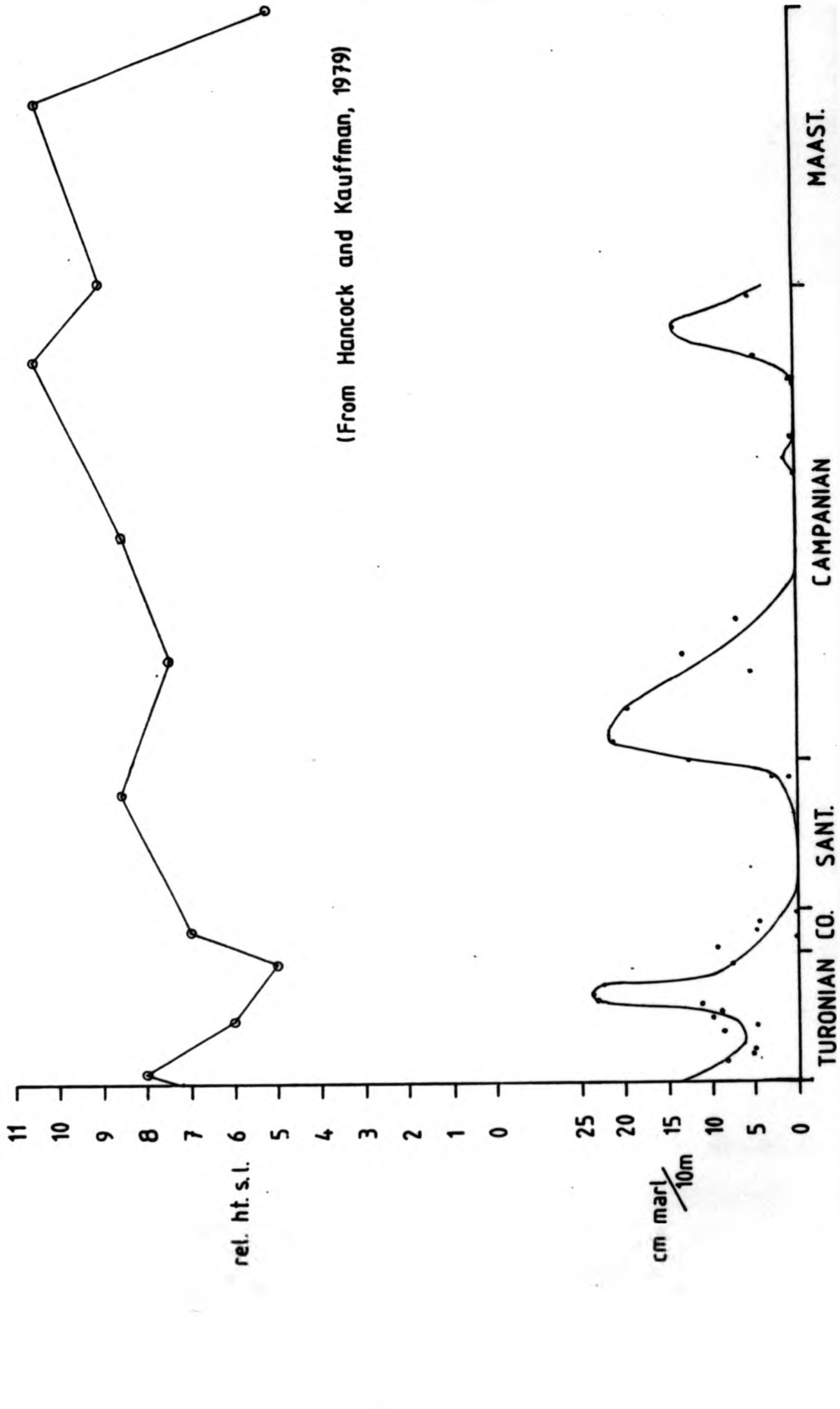
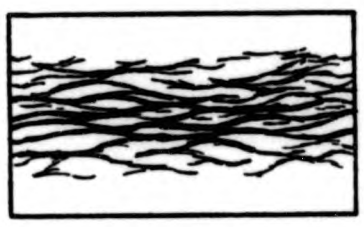


Figure 2.4

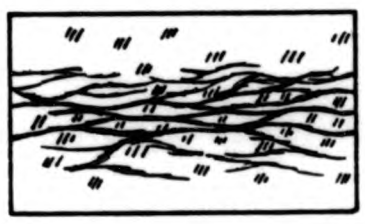
A CLASSIFICATION OF MARL BANDS.

Type A

Type B

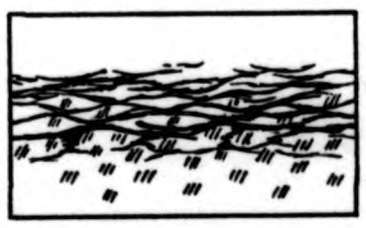


Type C



Type D

Type E



Type F

Figure 2.5

A MODEL OF MARL SEAM FORMATION.

1. Normal sedimentation.

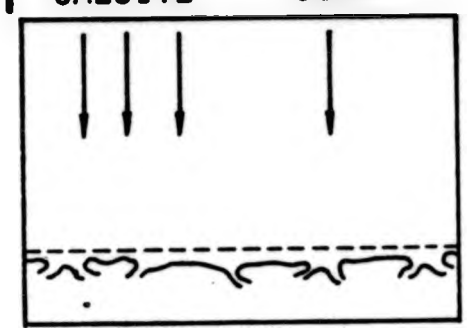
2. The carbonate:clay deposition ratio changes markedly, resulting in the deposition of a much more clay-rich sediment. The point at which this event commenced is marked by a more clay-rich notch slightly above the apparent base of the seam. Burrows are infilled with the sediment.

3. The carbonate:clay deposition ratio shifts slightly back towards 'normal conditions', but reworking of the keeps clay at an artificially high level.

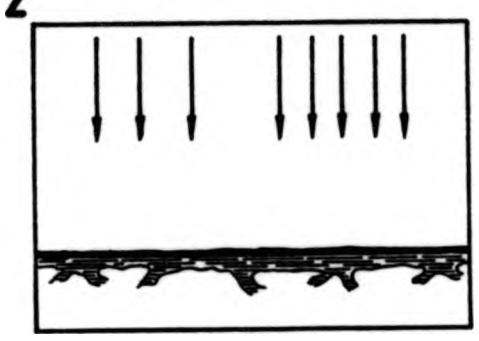
4. The return to normal depositional conditions appear to be gradational, this is partly because of the upwards reworking of some of the more clay-rich sediment.

5. Burrows enter the more marly chalk from above, reworking it, and carry small amounts of material upwards.

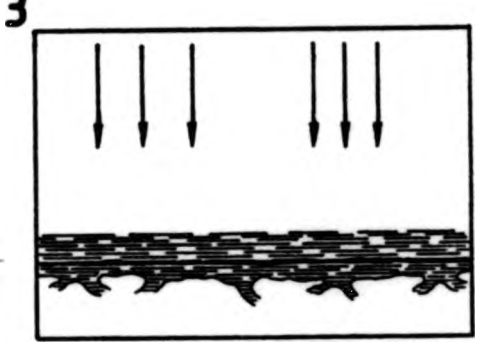
1 CALCITE CLAY



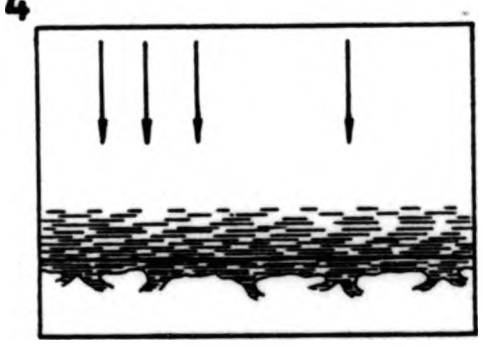
2



3



4



5

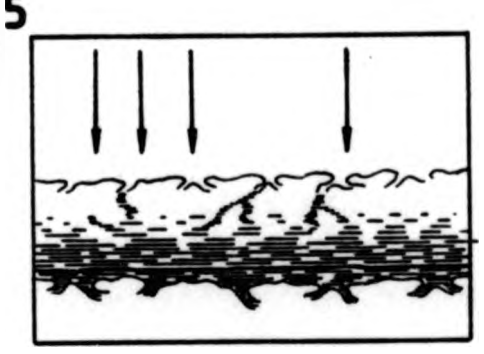


Figure 2.6

A MODEL OF FLASER MARL FORMATION THROUGH INTERMITTENT DEPOSITION OF MARLY CHALK.

1. Normal deposition

2. Deposition of a thin, more clay-rich unit which is reworked, diluted, and infills burrows.

3. Recommencement of white chalk deposition, some of the marly chalk is reworked upwards.

4. Deposition of a further, thin clay-rich unit.

5. Return to white chalk deposition.

6. Deposition of yet more clay.

7. Return to white chalk deposition.

8. Subsequent compaction, deformation and pressure solution produces a flaser marl.

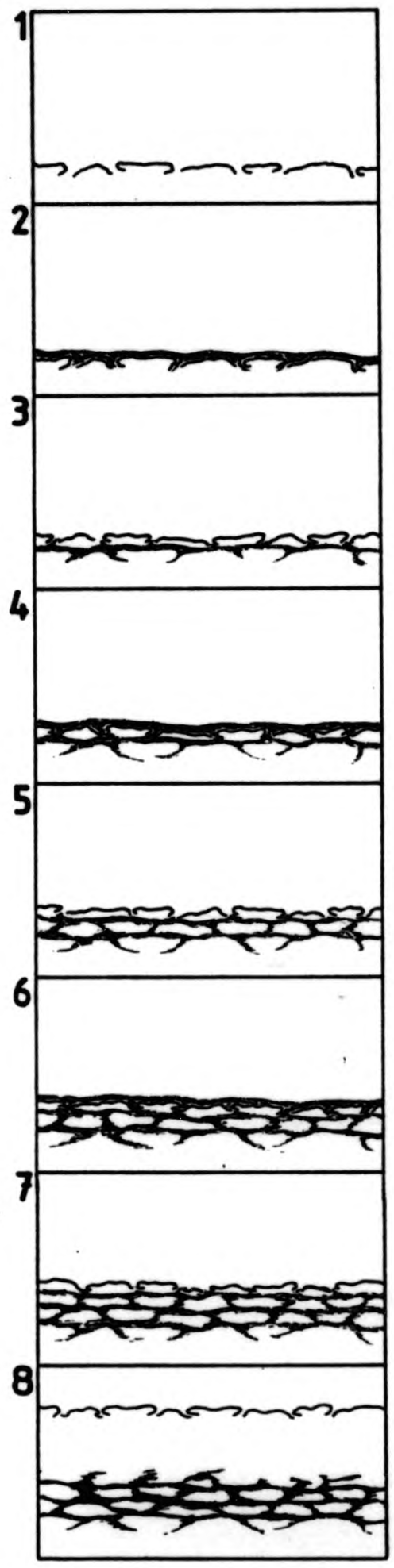

1
2
3
4
5
6
7
8

Figure 2.7

STAGES IN THE DEVELOPMENT OF AN OMISSION OR EROSION SURFACE AND THE OVERLYING SEDIMENTS.

1. Normal conditions (dashed line indicates the actual sediment-water interface, the mixed layer occurs between the dashed and solid lines).

2. Carbonate deposition decreases or stops, and by default the sediment in the mixed layer becomes more clay-rich. Burrow infills also reflect the increase in the proportion of clay. After a short period of time weak nodules may develop below the mixed layer.

3. A continuation of these conditions results in the mixed layer becoming even more clay-rich, and firm nodules develop below it.

4. After the gradual or sudden recommencement of carbonate deposition, reworking upwards of part of the clay-rich mixed layer gives rise to a more gradational transition back into white chalk than would otherwise be expected.

5. An increase in current activity during either stage 2 or 3 results in non-deposition of material and winnowing of the fine fraction which has already been deposited. The effect of this is to produce a coarse basal lag which rests on the erosion surface and infills the omission suite of burrows. Extended exposure results in the formation of nodules.

6. Assuming that the increase in current activity is brief, deposition of clay-rich chalk will commence again. Bioturbation may partially homogenize the sediment, incorporating much of the coarse basal lag.

7. On returning to white chalk deposition, the more clay-rich sediment and the basal lag will be partially reworked upwards, giving rise to a lightening- and grading upwards sequence.

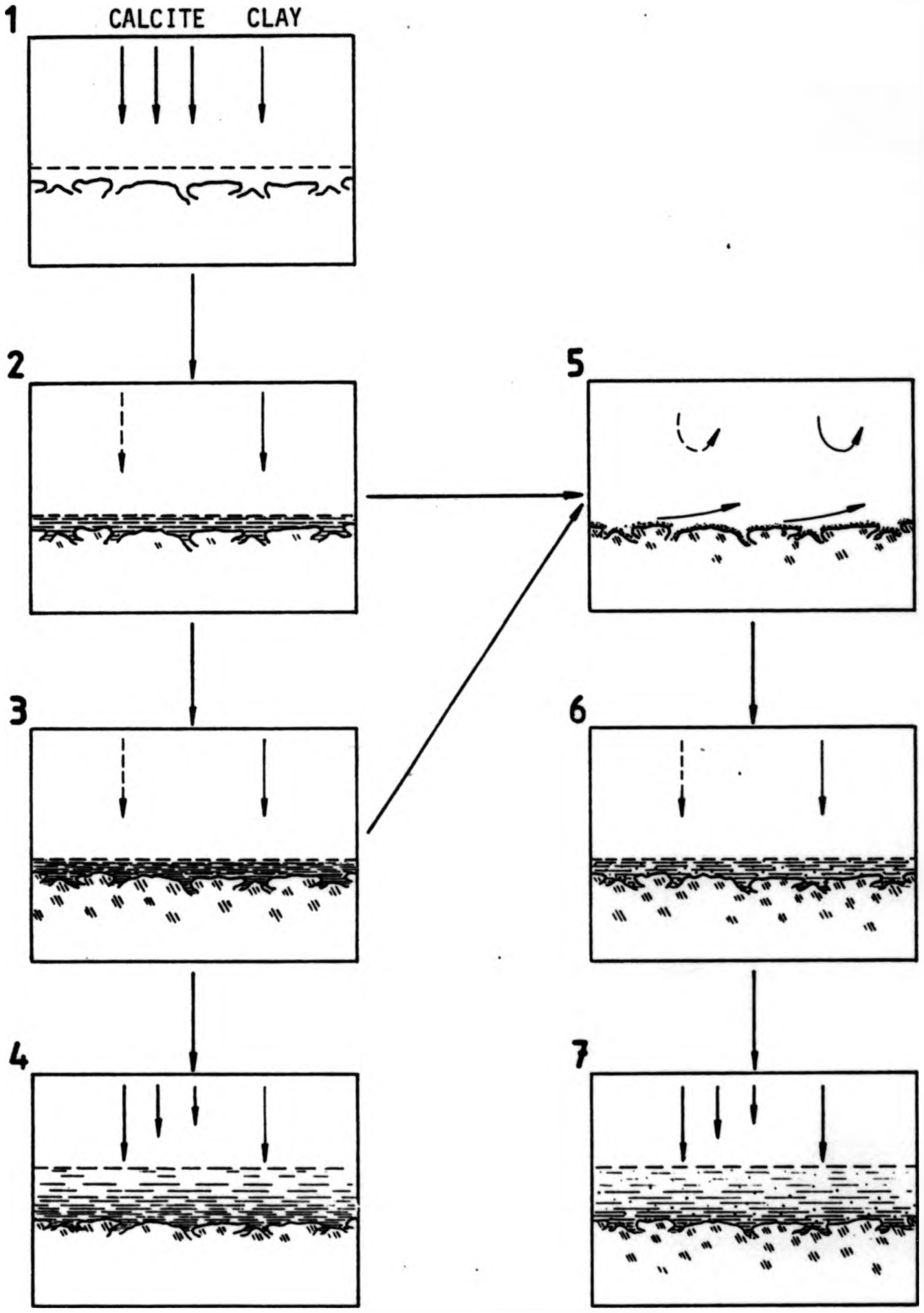

1
CALCITE
CLAY
2
3
4
5
6
7

Figure 2.8

CLASSIFICATION AND SUMMARY OF OMISSION AND EROSION SURFACES.

1. An omission surface, formed due to a brief break or sharp decrease in carbonate sedimentation (dashed line indicates the actual sediment-water interface).

2. A nodular omission surface, formed due to an extended break in carbonate sedimentation.

3. A multiple nodular omission surface, formed if two or more omission surfaces are packed together.

4. If either a nodular- or multiple nodular omission surface is exposed for a long period of time a fully cemented omission surface (incipient hardground) is formed.

5. Exposure and erosion of an omission surface produces an erosion surface with a basal lag of coarse material.

6. Exposure and erosion of a nodular omission surface, or continued exposure of an erosion surface, produces a nodular erosion surface with a coarse lag deposit and possibly some mineralization (illustrated by the thick black line). Exposure and erosion of a multiple nodular omission surface results in transformation of the uppermost surface.

7. Renewed deposition followed by further erosion produces a multiple nodular erosion surface.

8. Continued erosion of a nodular- or multiple nodular erosion surface, or erosion and exposure of an incipient hardground, produces a hardground which is usually mineralized and whose burrows are infilled with a coarse basal lag. A hardground may incorporate several breaks in sedimentation.

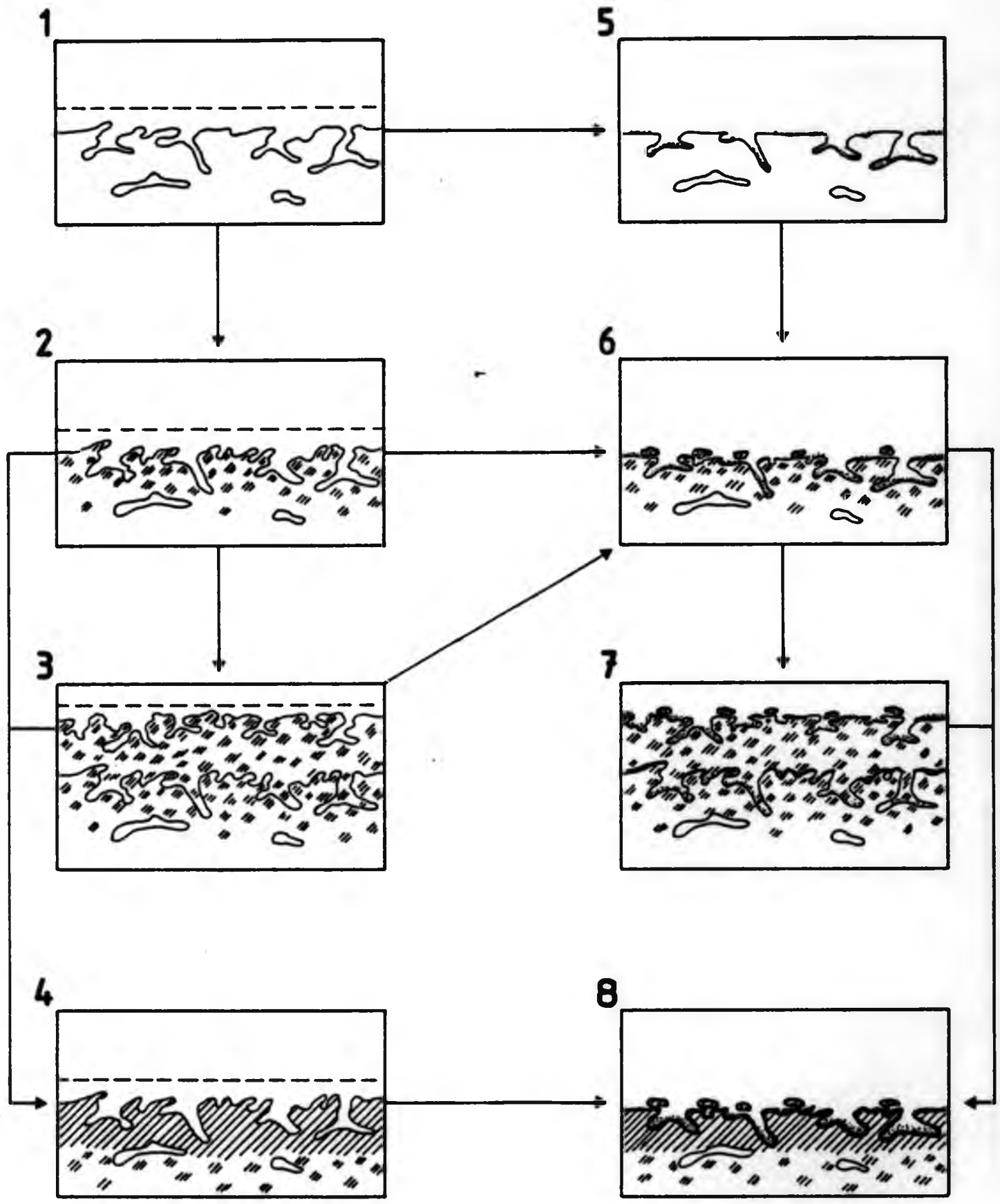
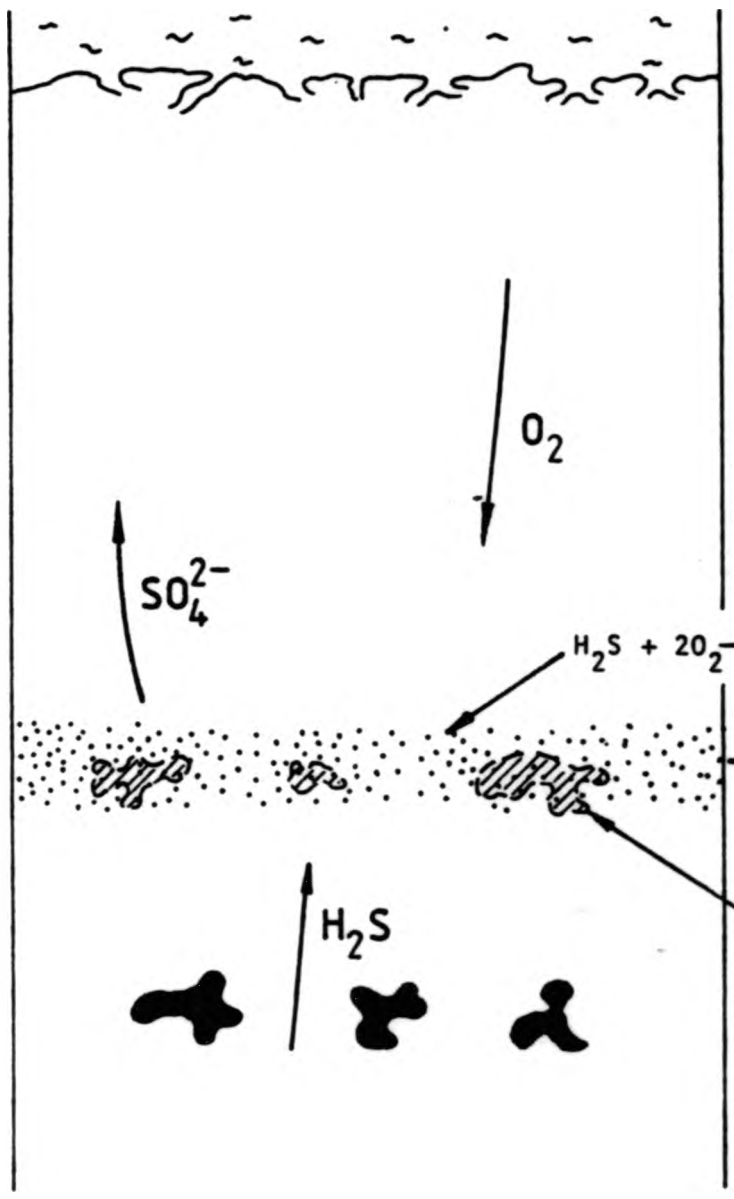

1
5
2
6
3
7
4
8

Figure 2.9

A MODEL OF FLINT FORMATION (after Clayton, 1986).



BIOGENIC OPAL READILY DISSOLVES IN THE SEDIMENT AS IT IS HIGHLY UNSATURATED WITH RESPECT TO AMORPHOUS SILICA. IT MAY BE SATURATED WITH RESPECT TO CRYSTALLINE SILICA.

SILICA DISSOLUTION OUTPACES PRECIPITATION RESULTING IN A CONCENTRATED SILICA SOLUTION.

DISSOLUTION OF CARBONATE TAKES PLACE AT THE OXIC-ANOXIC BOUNDARY DUE TO THE PRODUCTION OF HYDROGEN IONS.

THE CARBONATE IONS RELEASE ACT AS SEEDING AGENTS FOR THE PRECIPITATION OF SILICA IN THE FORM OF FLINT.

THE SILICA IS PREFERENTIALLY FOUND IN BURROWS BECAUSE OF THEIR HIGHER ORGANIC CONTENT AND POROSITY

Figure 2.10

DIAGRAM SHOWING HOW CEMENTATION CONTROLS THE VARIATION IN POSITION AND FORM OF FLASERS FORMED BY PRESSURE SOLUTION.

1. In soft chalk flasers are weak and occur below omission surfaces.

2. With the development of weak nodules flasers are again only found below the omission surface, but they are better developed.

3. A further slight increase in nodularity gives rise to well formed flasers below the surface and the development of weak flasers on the surface.

4. Continued increases in nodularity results in flasers extending downwards, and flasers above the surface become better developed and drape around nodules.

5. Where nodules coalesce to form a framework, flaser development is prevented. Flasers become well developed in the soft chalk above the surface and also in the soft or weakly nodular chalk below the cemented framework.

6. If the sediment below the surface is fully lithified, flaser development only occurs above the surface. Flasers are not usually found draped on the surface.

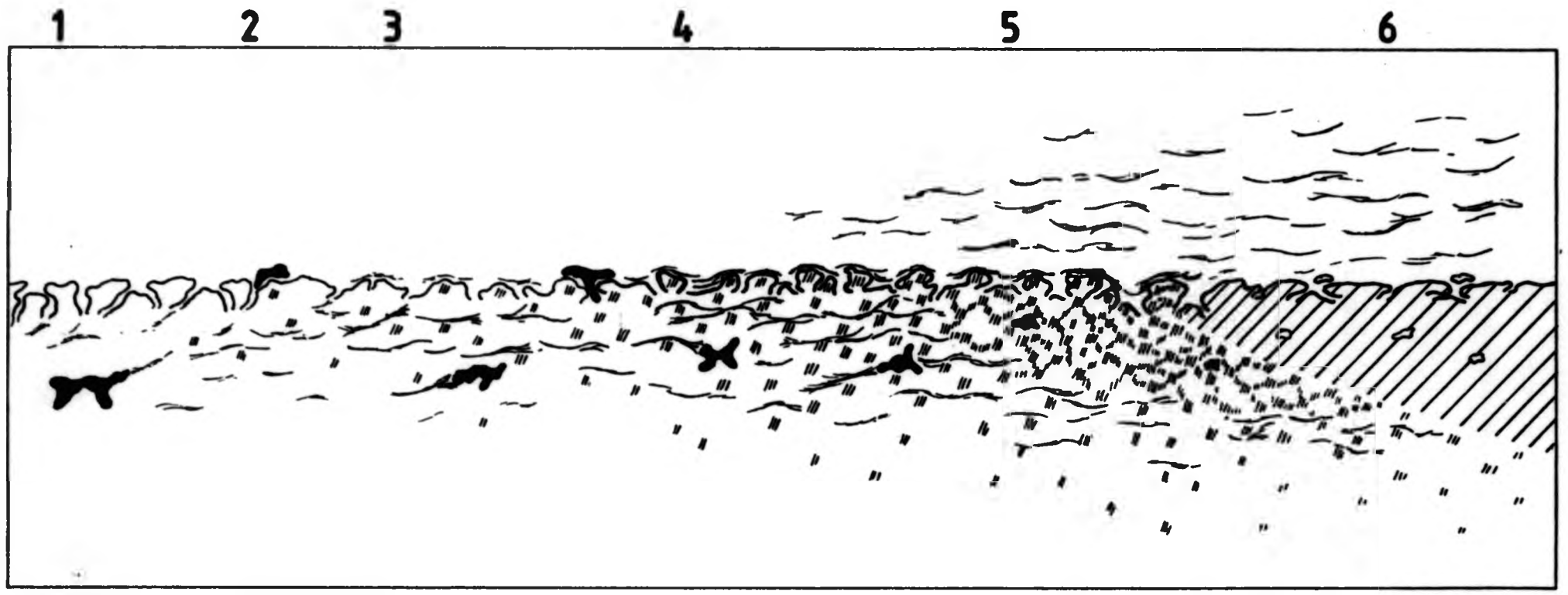

1
2
3
4
5
6

Figure 3.1a and b

X-RAY DIFFRACTION TRACES OF INSOLUBLE RESIDUES ACROSS NEW PIT MARLS 1 AND 2 FROM BEACHY HEAD.

Although both the smectite and illite increase within the marl seam, the increase in smectite is slightly larger than the increase in illite.

15.49Å to 15.22Å	smectite.
10.04Å to 9.9Å	illite
7.10Å	kaolinite
5.0Å	illite
4.26Å	quartz
3.34Å	quartz and illite
3.04Å	calcite

Figure 3.1a

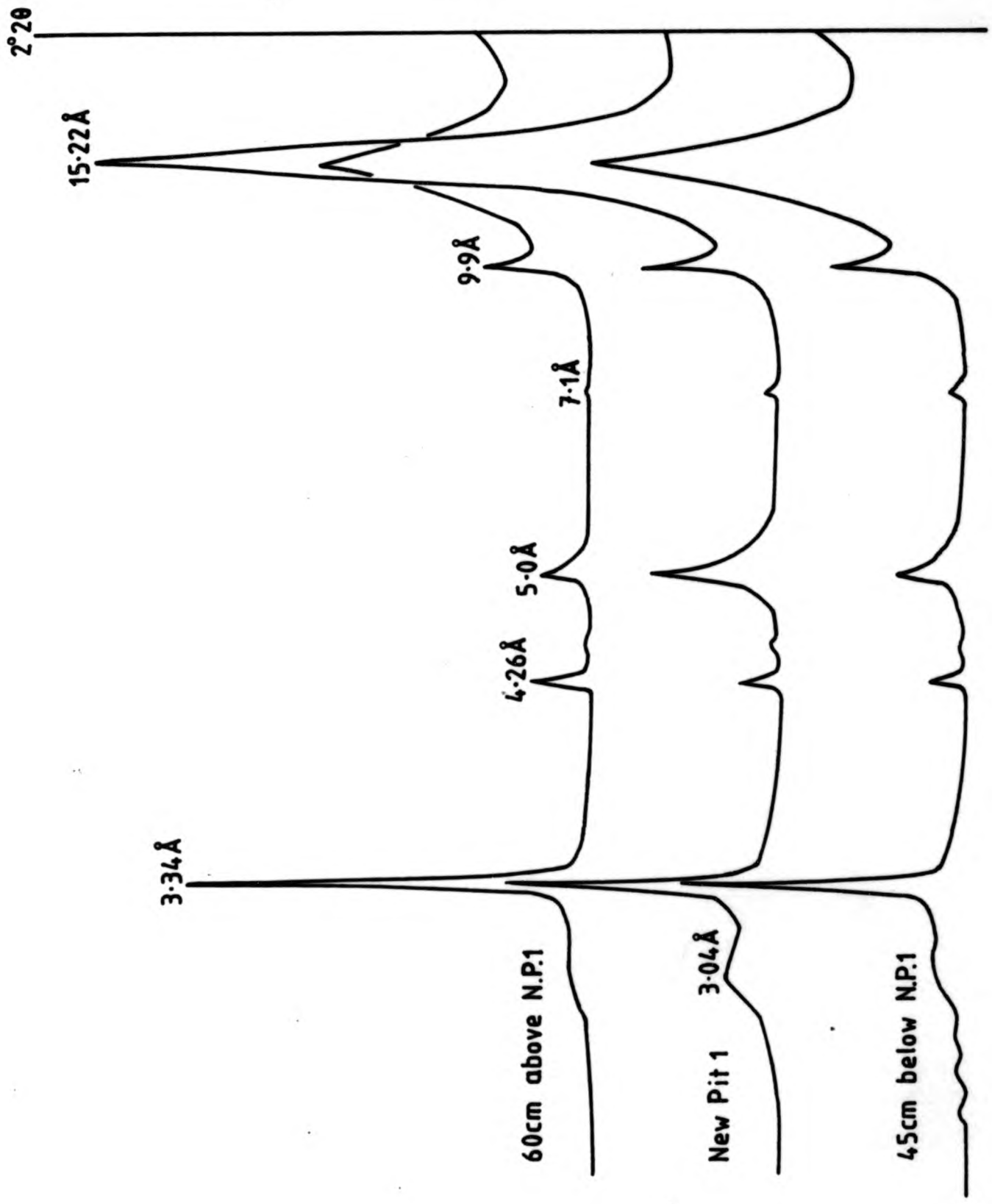

2°2θ
15·22Å
9·9Å
7·1Å
5·0Å
4·26Å
3·34Å
60cm above N.P.1
New Pit 1
3·04Å
45cm below N.P.1

Figure 3.1b

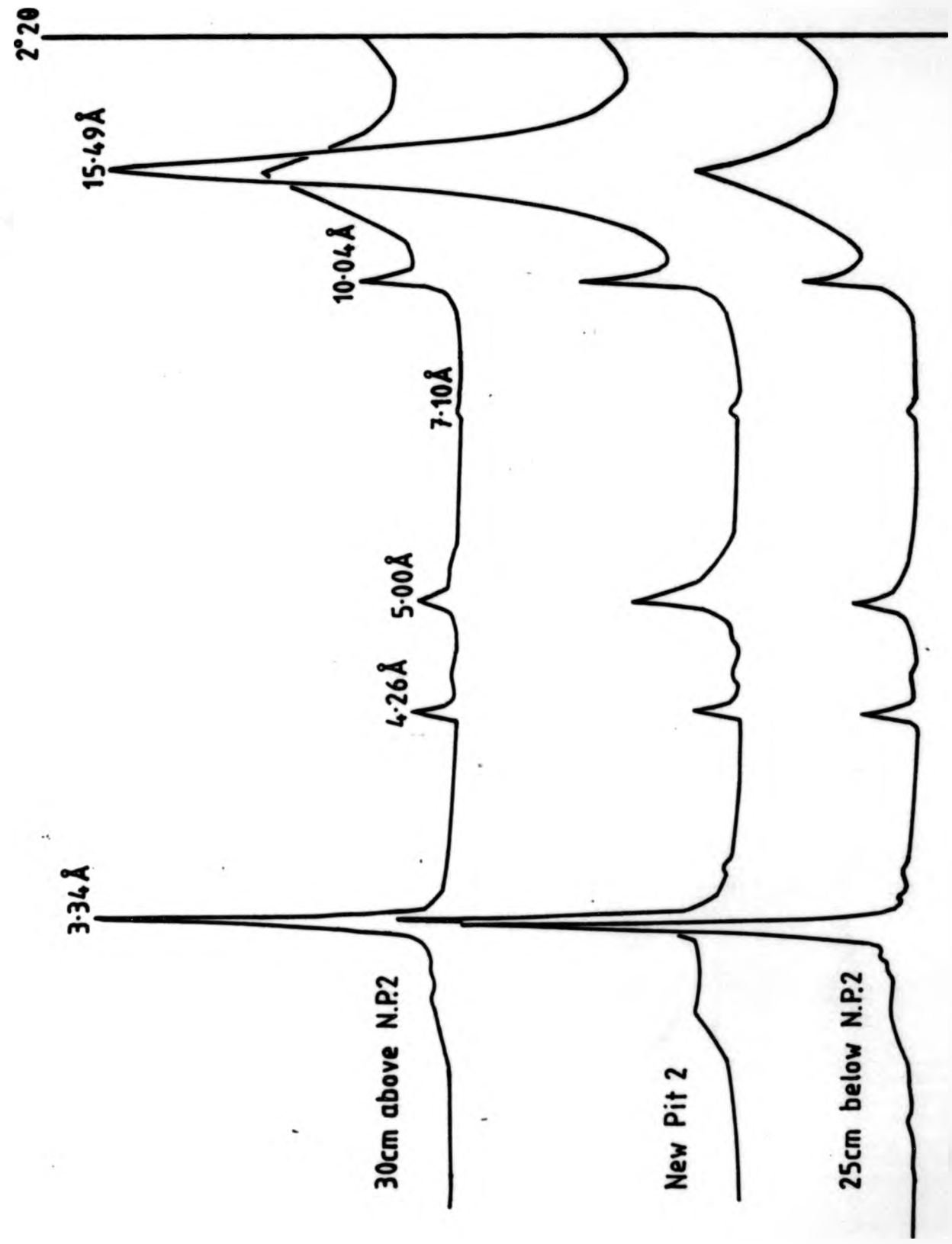

2°20
15·49Å
10·04Å
4·26Å
5·00Å
7·10Å
3·34Å
30cm above N.P.2
New Pit 2
25cm below N.P.2

Figure 3.2a and b

X-RAY DIFFRACTION TRACES OF INSOLUBLE RESIDUES OF LOWER AND MIDDLE TURONIAN MARLS FROM SUSSEX.

All show great similarity in composition and relatively low smectite:illite ratios. Note that kaolinite is only occurs, in trace amounts, in Malling Street Marl 1.

15.22Å	smectite.
9.93Å to 10.04Å	illite
7.08Å	kaolinite
5.0Å	illite
4.50Å	smectite
4.24Å to 4.26Å	quartz
3.34Å	quartz and illite
3.04Å	calcite

Figure 3.2a

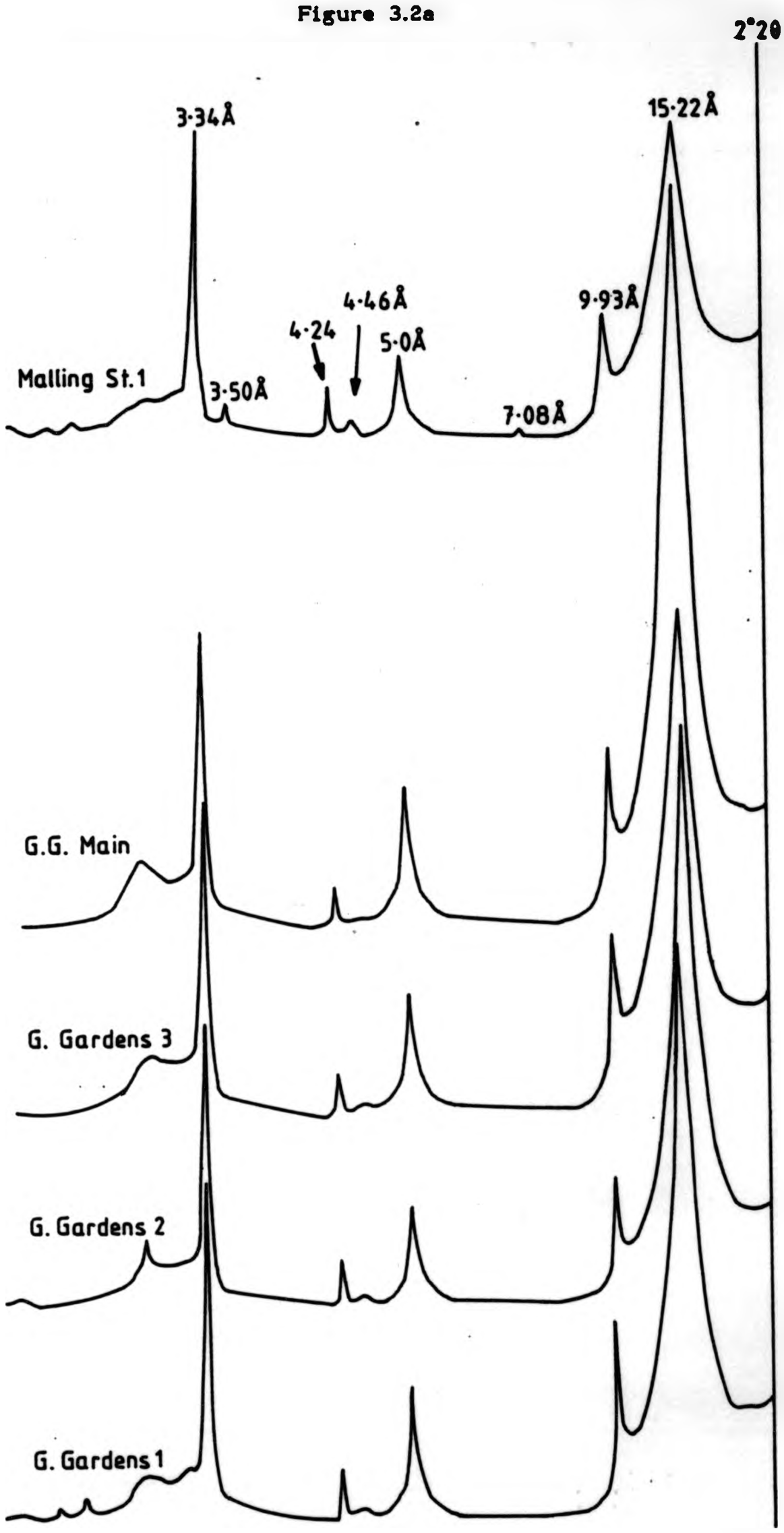

2°2θ
3·34Å
15·22Å
4·46Å
9·93Å
4·24
5·0Å
Malling St.1
3·50Å
7·08Å
G.G. Main
G. Gardens 3
G. Gardens 2
G. Gardens 1

Figure 3.2b

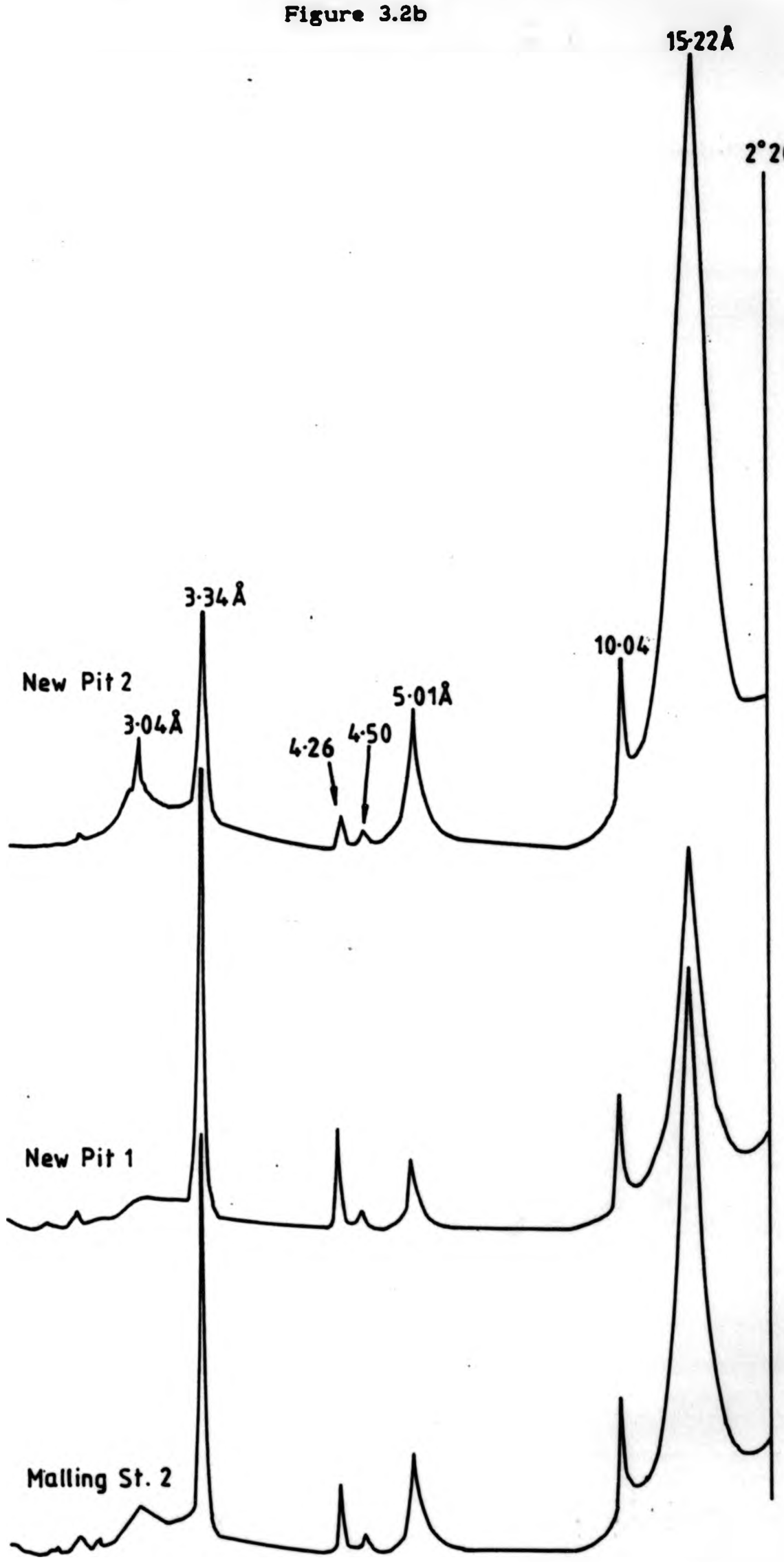

15·22Å
2°2θ
3·34Å
10·04
New Pit 2
3·04Å
5·01Å
4·26
4·50
New Pit 1
Malling St. 2

Figure 3.3a and b

X-RAY DIFFRACTION TRACES OF INSOLUBLE RESIDUES OF SOME MIDDLE AND UPPER TURONIAN MARLS FROM SUSSEX.

All show significantly higher, but variable, smectite:illite ratios when compared to stratigraphically lower marls. Note also the complete absence of kaolinite.

15.49Å to 15.22Å	smectite.
9.98Å	illite
5.0Å	illite
4.48Å	smectite
4.26Å to 4.23Å	quartz
3.35Å	quartz and illite
3.05Å to 3.02Å	calcite
2.79Å and 2.69Å	carbonate-apatite.

Figure 3.3a

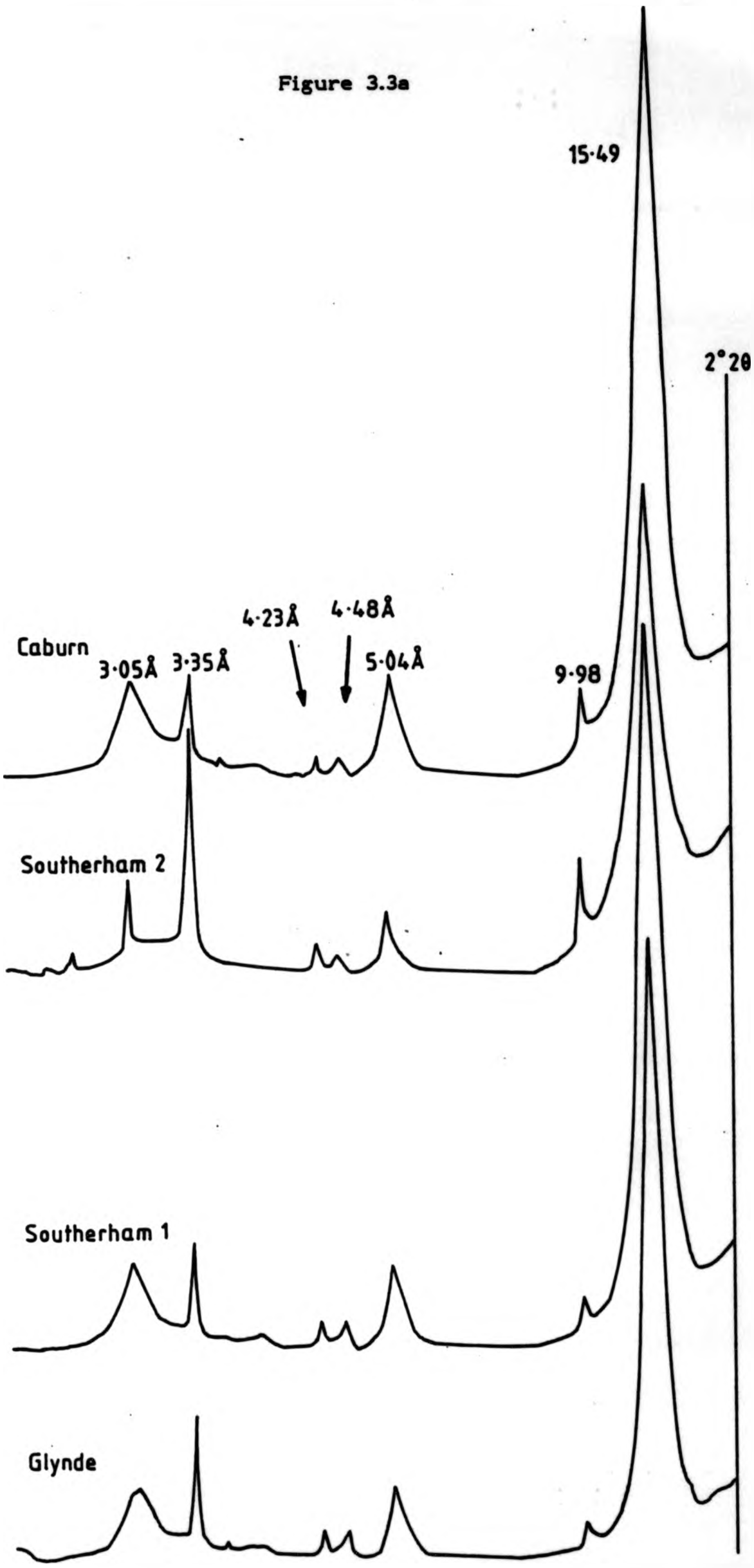

15·49
2°20
4·23Å
4·48Å
Caburn
3·05Å
3·35Å
5·04Å
9·98
Southerham 2
Southerham 1
Glynde

Figure 3.3b

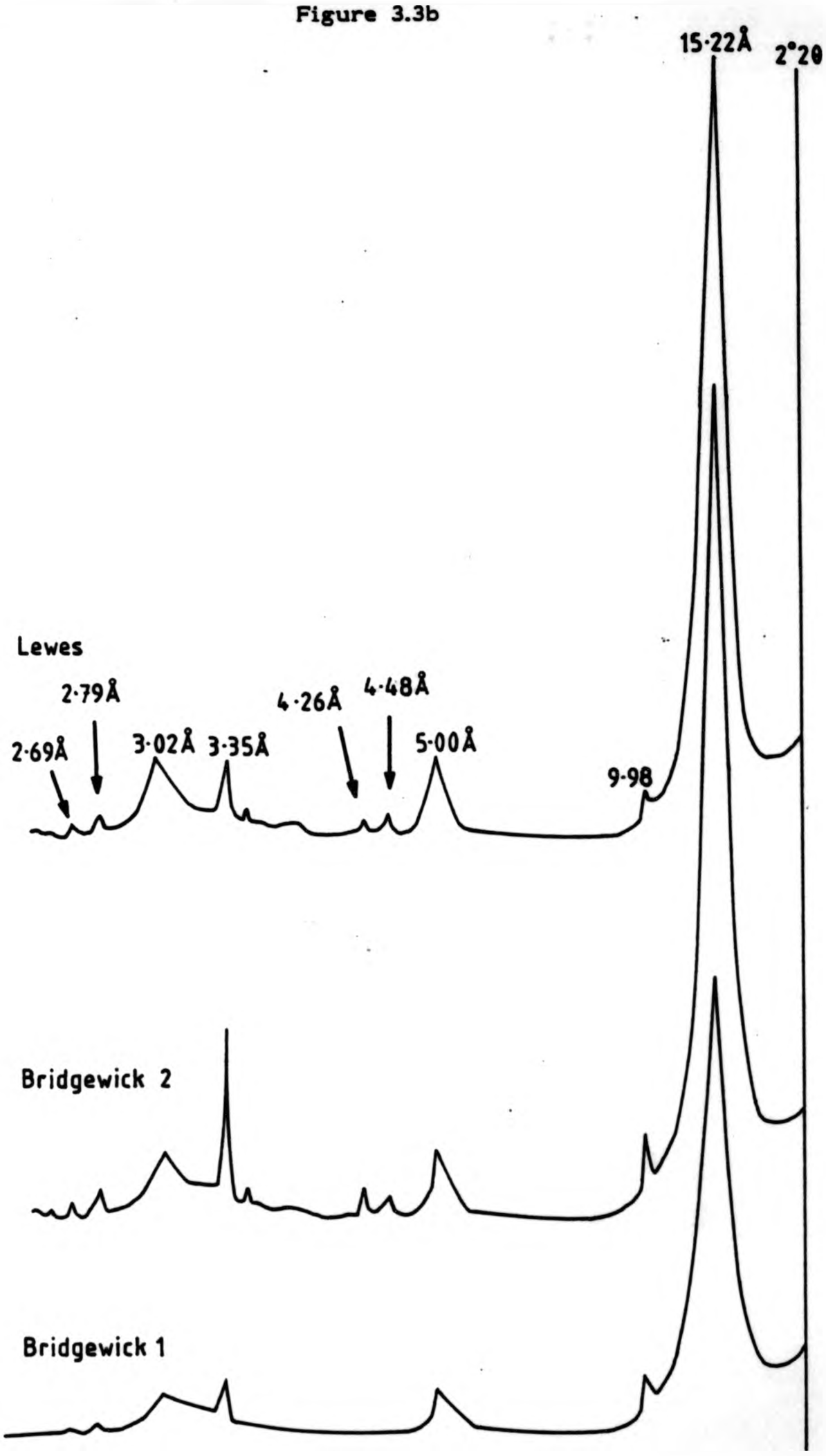

15·22Å
2°2θ
Lewes
2·79Å
2·69Å
3·02Å
3·35Å
4·26Å
4·48Å
5·00Å
9·98
Bridgewick 2
Bridgewick 1

Figure 3.4a, b and c

X-RAY DIFFRACTION TRACES OF INSOLUBLE RESIDUES OF MIDDLE AND UPPER TURONIAN MARLS FROM DOVER, KENT.

Note the similarity in composition between the Sussex and Kent samples and the sharp increase in smectite:illite ratios above New Pit Marl 2.

15.22Å to 15.10Å	smectite.
10.04Å	illite
5.0Å	illite
4.50Å	smectite
4.25Å	quartz
3.34Å	quartz and illite
3.05Å to 3.02Å	calcite
2.79Å and 2.69Å	carbonate-apatite.

Figure 3.4a

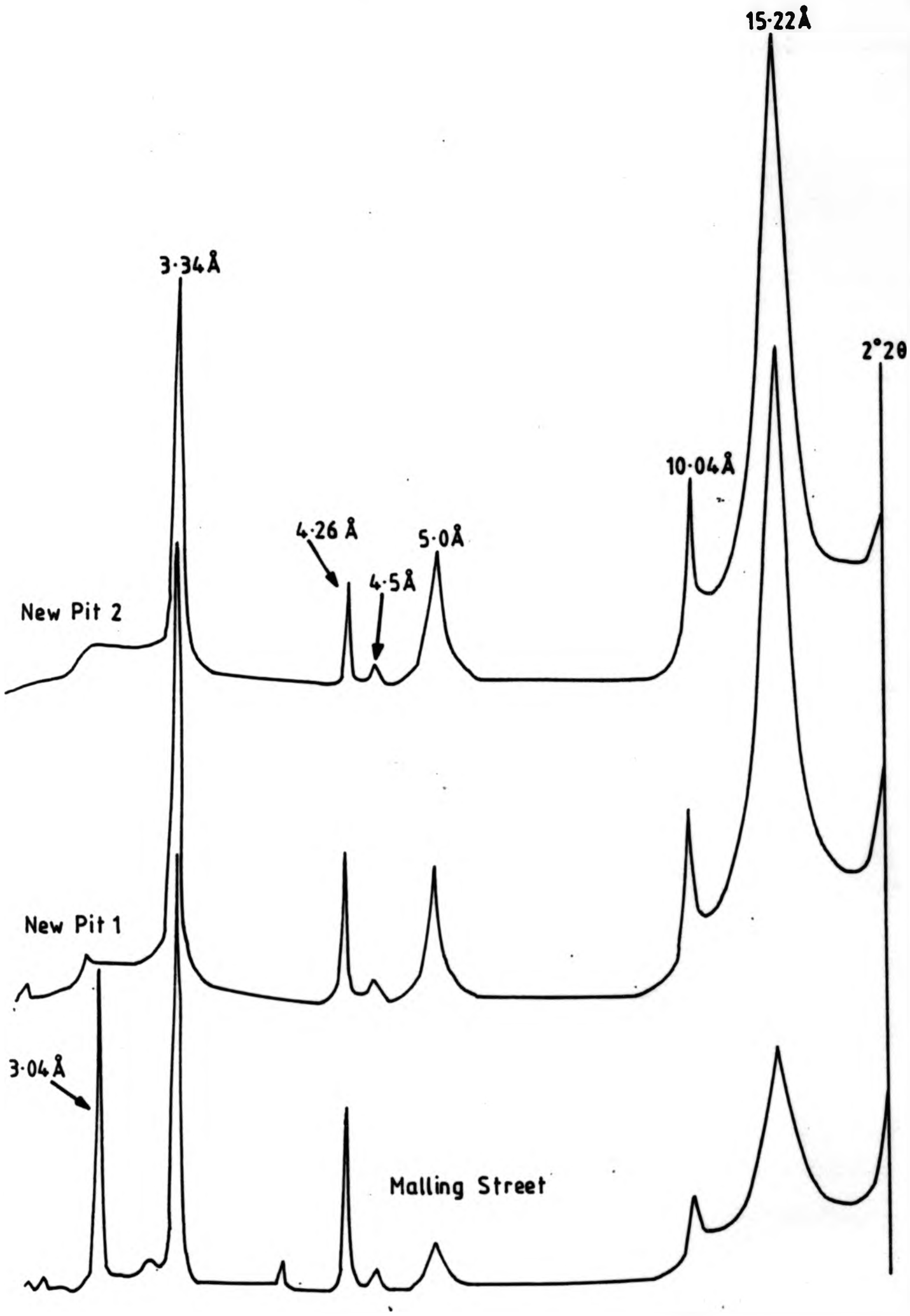

15·22Å
3·34Å
2°2θ
10·04Å
4·26 Å
5·0Å
4·5Å
New Pit 2
New Pit 1
3·04Å
Malling Street

Figure 3.4b

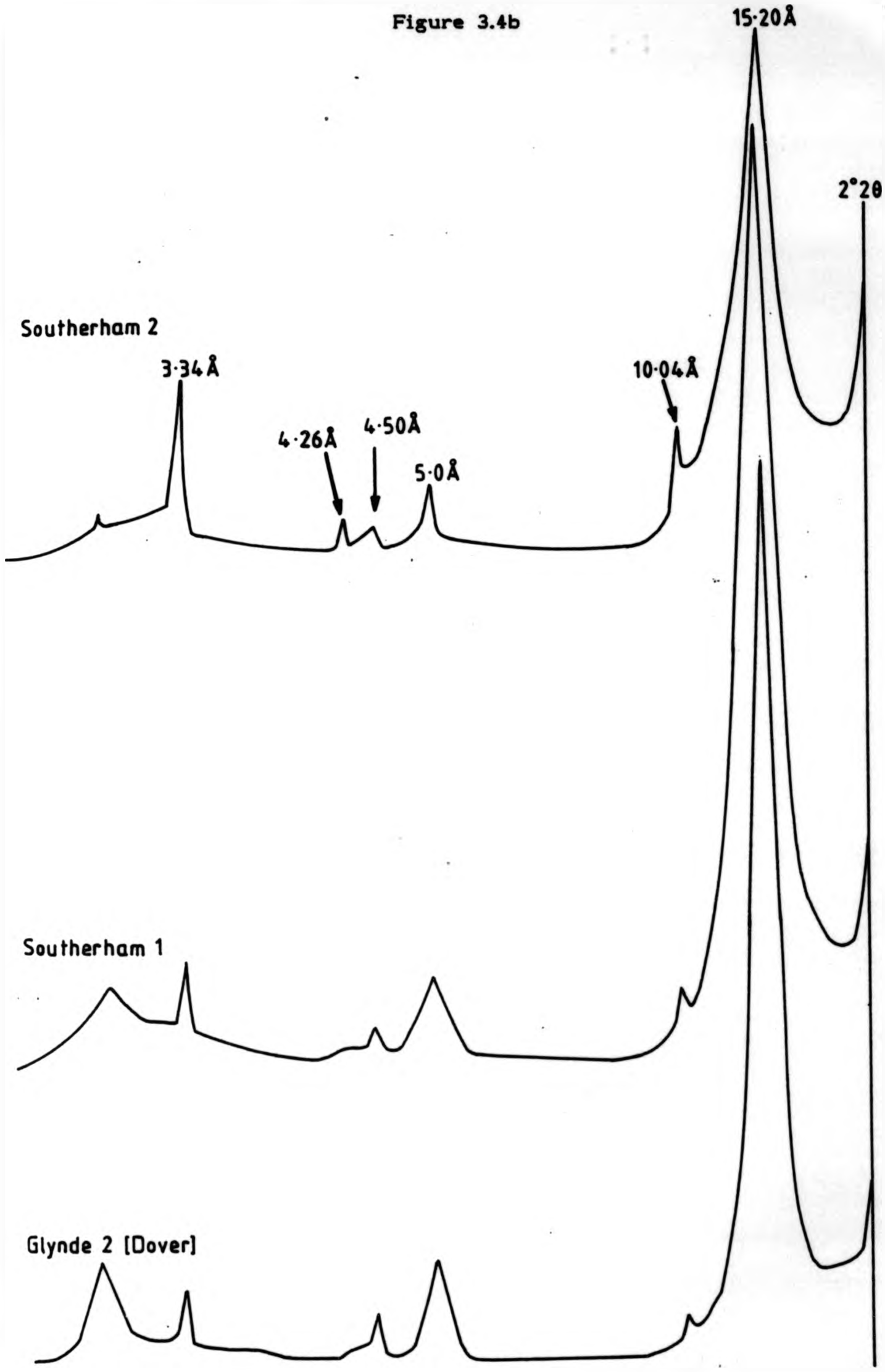

15·20Å
2°2θ
Southerham 2
3·34Å
10·04Å
4·26Å
4·50Å
5·0Å
Southerham 1
Glynde 2 [Dover]

Figure 3.4c

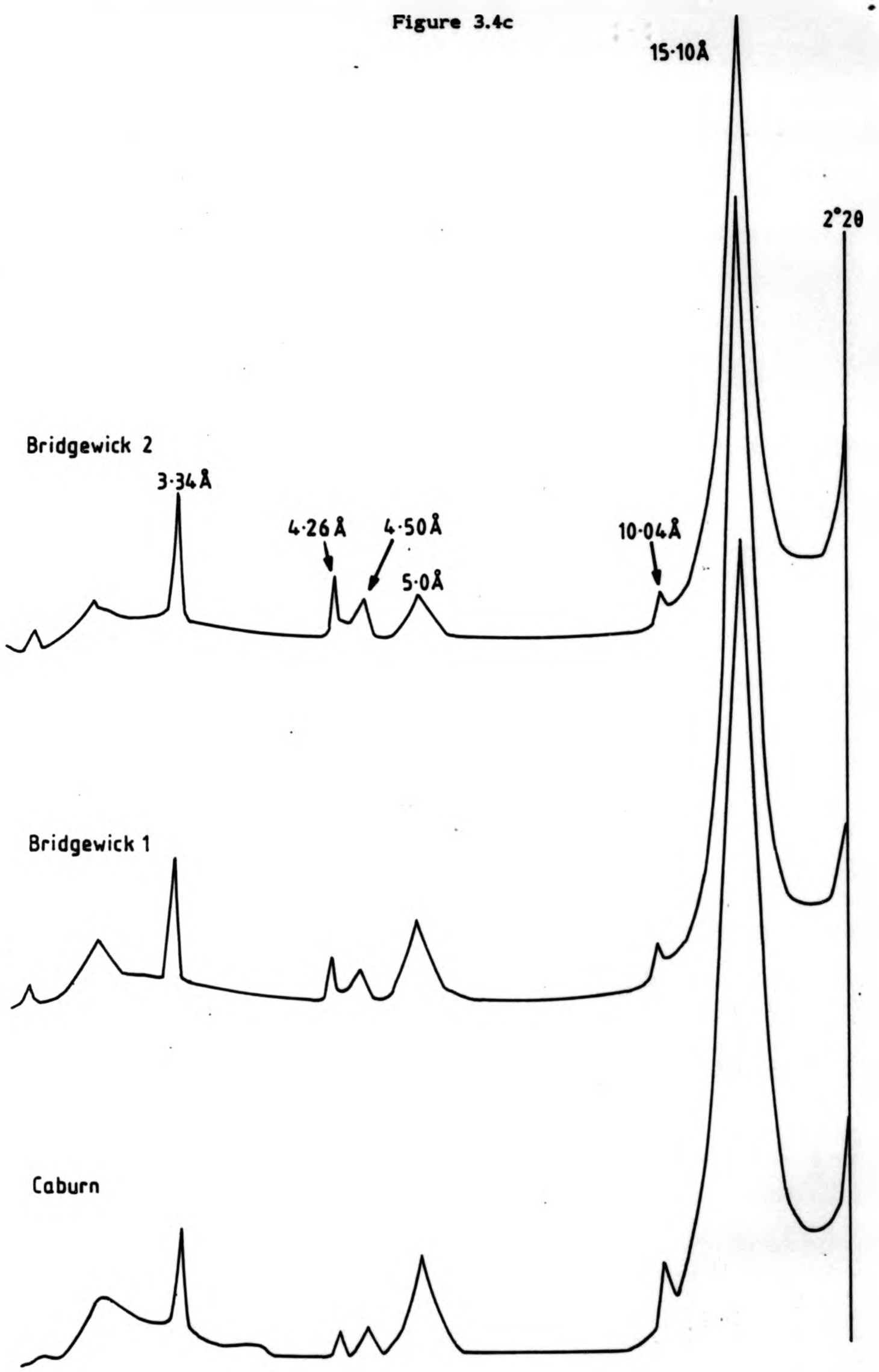

15·10Å
2°2θ
Bridgewick 2
3·34Å
4·26Å
4·50Å
5·0Å
10·04Å
Bridgewick 1
Caburn

Figure 3.5a, b and c

X-RAY DIFFRACTION TRACES OF INSOLUBLE RESIDUES OF MIDDLE AND UPPER TURONIAN MARLS AND ADJACENT WHITE CHALKS FROM PUYS, FRANCE

Note the similar mineralogy of the white and marly chalks. Note also the difference in smectite:illite ratios between adjacent white and marly chalks, a difference which becomes more pronounced up-section. Clinoptinolite may be derived from the alteration of volcanic ash, it occurs in both white and marly chalks.

15.49Å to 15.22Å	smectite.
10.15Å to 10.04Å	illite
8.97Å to 9.0Å	clinoptinolite
7.89Å	clinoptinolite
5.0Å	illite
4.48Å	smectite
4.26Å to 4.23Å	quartz
3.97Å	clinoptinolite
3.34Å	quartz and illite
3.05Å to 3.02Å	calcite
2.79Å and 2.69Å	carbonate-apatite.

Figure 3.5a

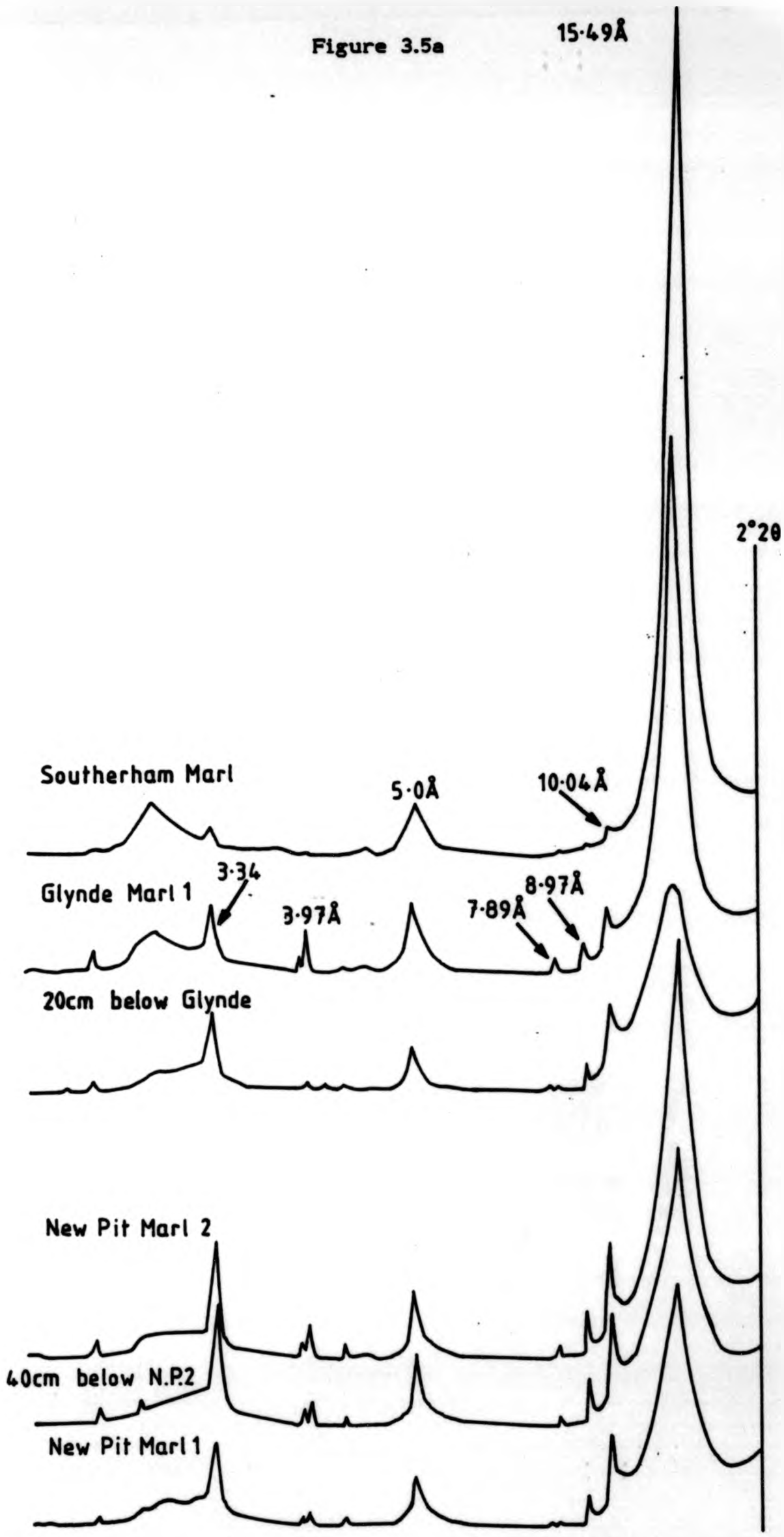

15·49Å
2°2θ
Southerham Marl
5·0Å
10·04Å
Glynde Marl 1
3·34
3·97Å
7·89Å
8·97Å
20cm below Glynde
New Pit Marl 2
40cm below N.P.2
New Pit Marl 1

Figure 3.5b

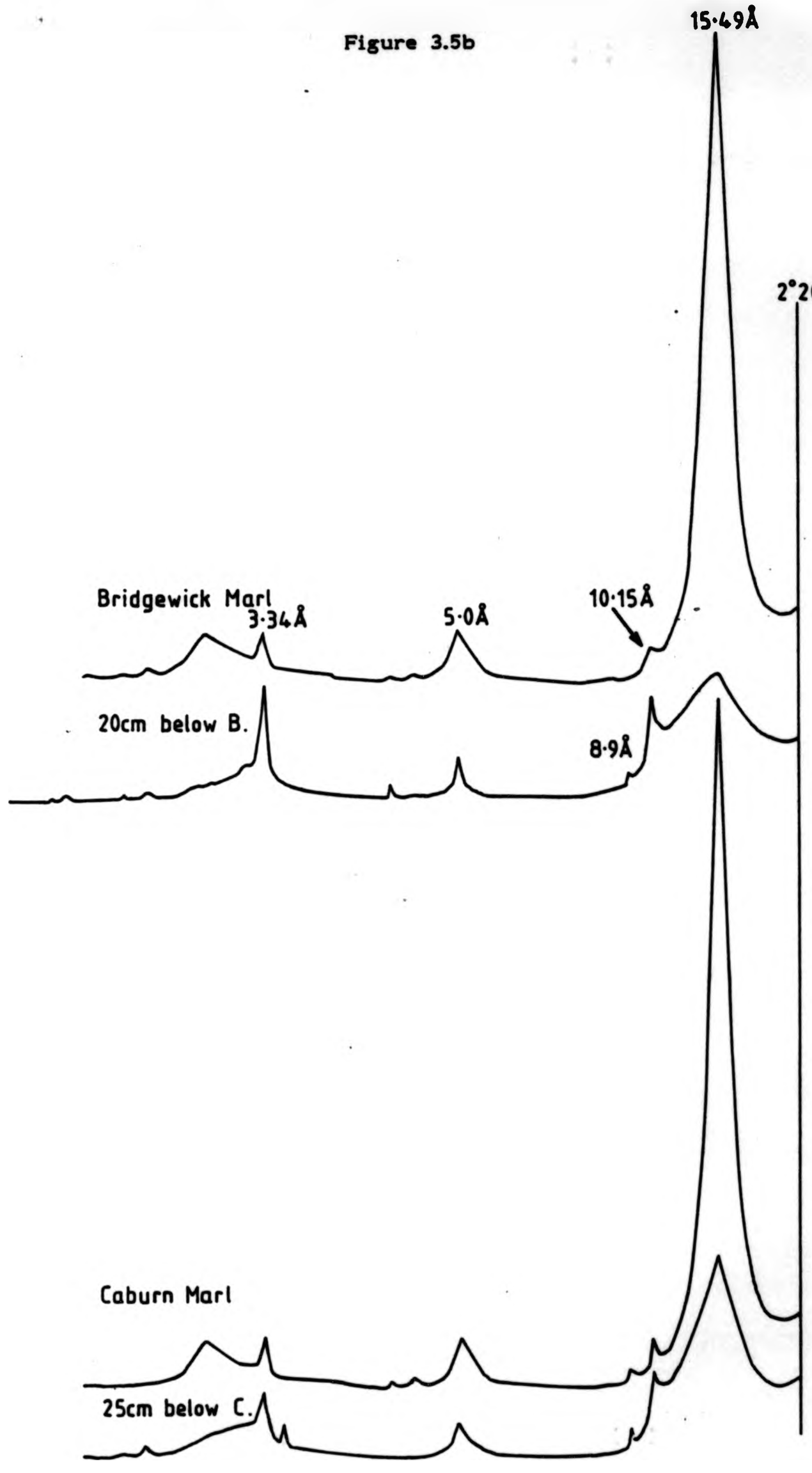

15·49Å
2°2θ
Bridgewick Marl
3·34Å
5·0Å
10·15Å
20cm below B.
8·9Å
Caburn Marl
25cm below C.

Figure 3.5c

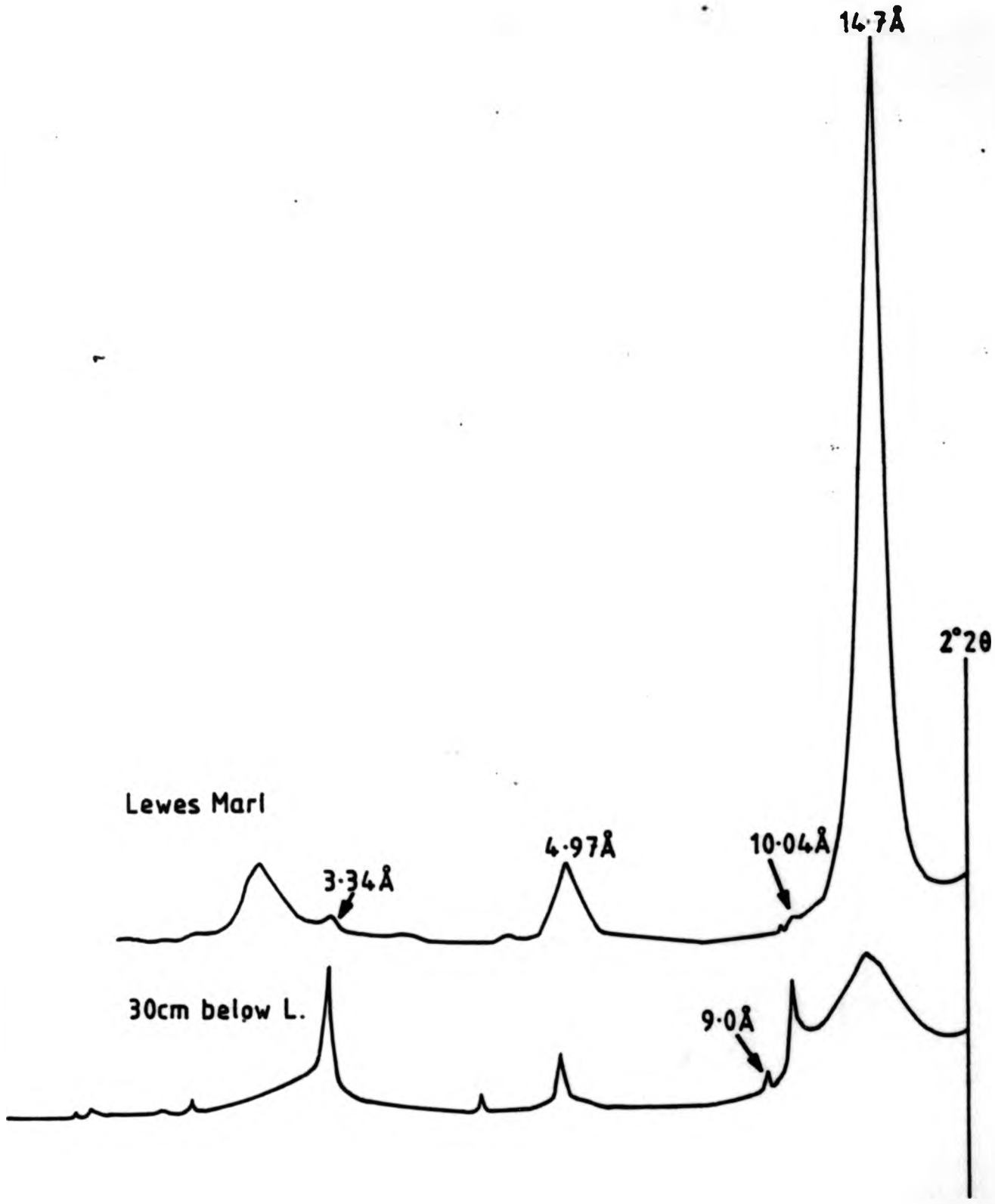


Figure 3.6

SMECTITE:ILLITE RATIOS OF MARLS FROM SUSSEX AND KENT, AND PAIRED WHITE AND MARLY CHALK RATIOS FROM FRANCE

Note the similarity in the patterns, especially the peak around the Glynde and Southerham Marls. Also note the near constant ratio of the white chalk samples from France.

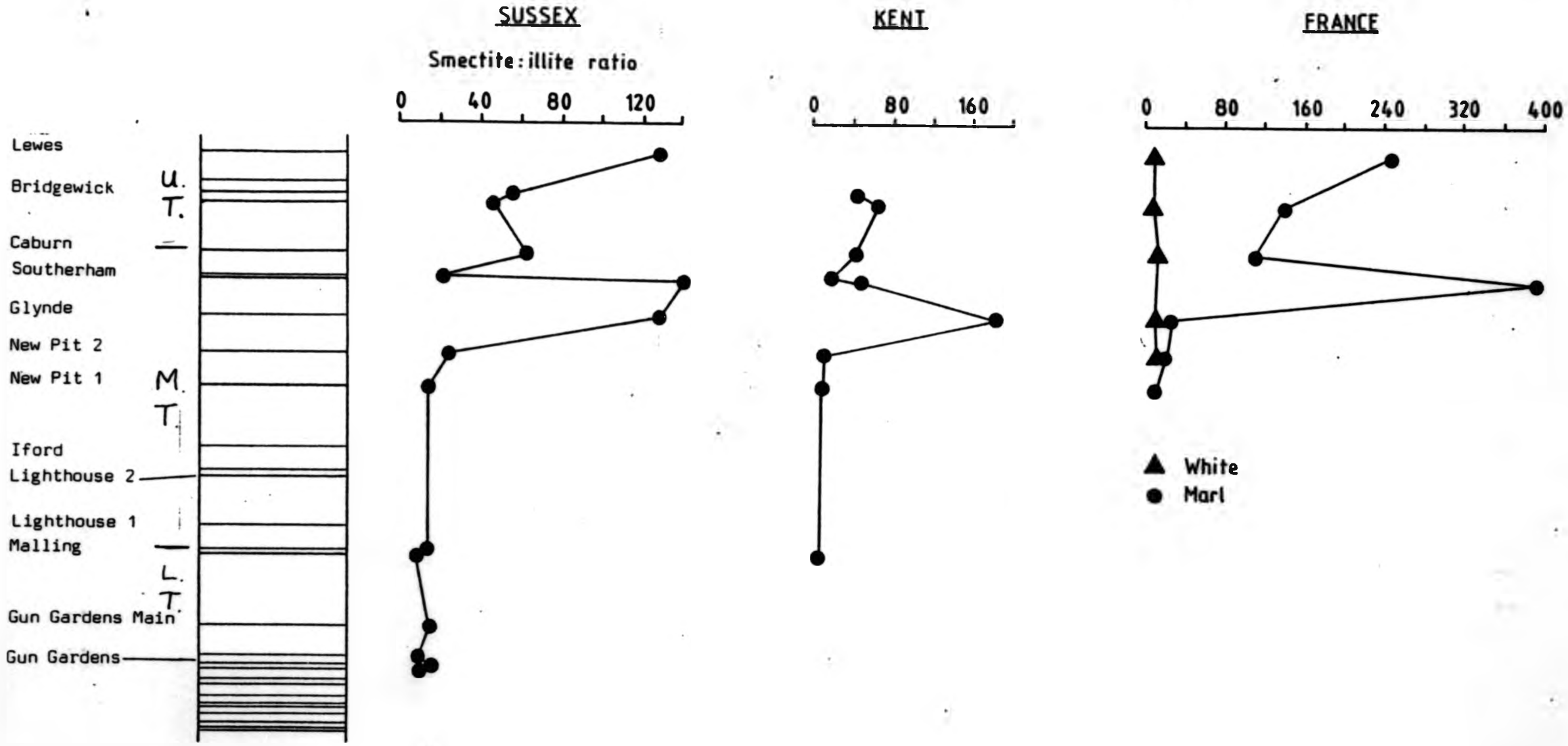

SUSSEX
Smectite : illite ratio
0 40 80 120
KENT
0 80 160
FRANCE
0 80 160 240 320 400
Lewes
Bridgewick
U. T.
Caburn
Southerham
Glynde
New Pit 2
New Pit 1
M. T.
Iford
Lighthouse 2
Lighthouse 1
Malling
L. T.
Gun Gardens Main
Gun Gardens
White
Marl

Figure 5.1

FORAMINIFERAL ASSEMBLAGES ACROSS THREE MIDDLE TURONIAN MARL BANDS

Foraminiferal assemblages across New Pit Marls 1 and 2, and Glynde Marl 1 from Burghclere. The planktonic/benthonic ratio decreases markedly within the marl seams, and within the planktonics the proportion of keeled forms increases. Epifaunal benthonic forms (gavellinellids and lenticulinids) decrease in number within marls whilst infaunal forms (tritaxids, marssonellids, eggerellinids and arenobuliminids) remain relatively constant. (Diagram adapted from Leary and Wray, 1989).

Key:

Above G1	35 cm above Glynde Marl 1
G1	Glynde Marl 1 [Caburn]
Below G1	30 cm below Glynde Marl 1
Above N.P.2	20 cm above New Pit Marl 2
N.P.2	New Pit Marl 2
Below N.P.2	10 cm below New Pit Marl 2
Above N.P.1	30 cm above New Pit Marl 1
N.P.1	New Pit Marl 1
Below N.P.1	20 cm below New Pit Marl 1

Test preservation:

* a little surface pitting

** small holes

*** extensive damage

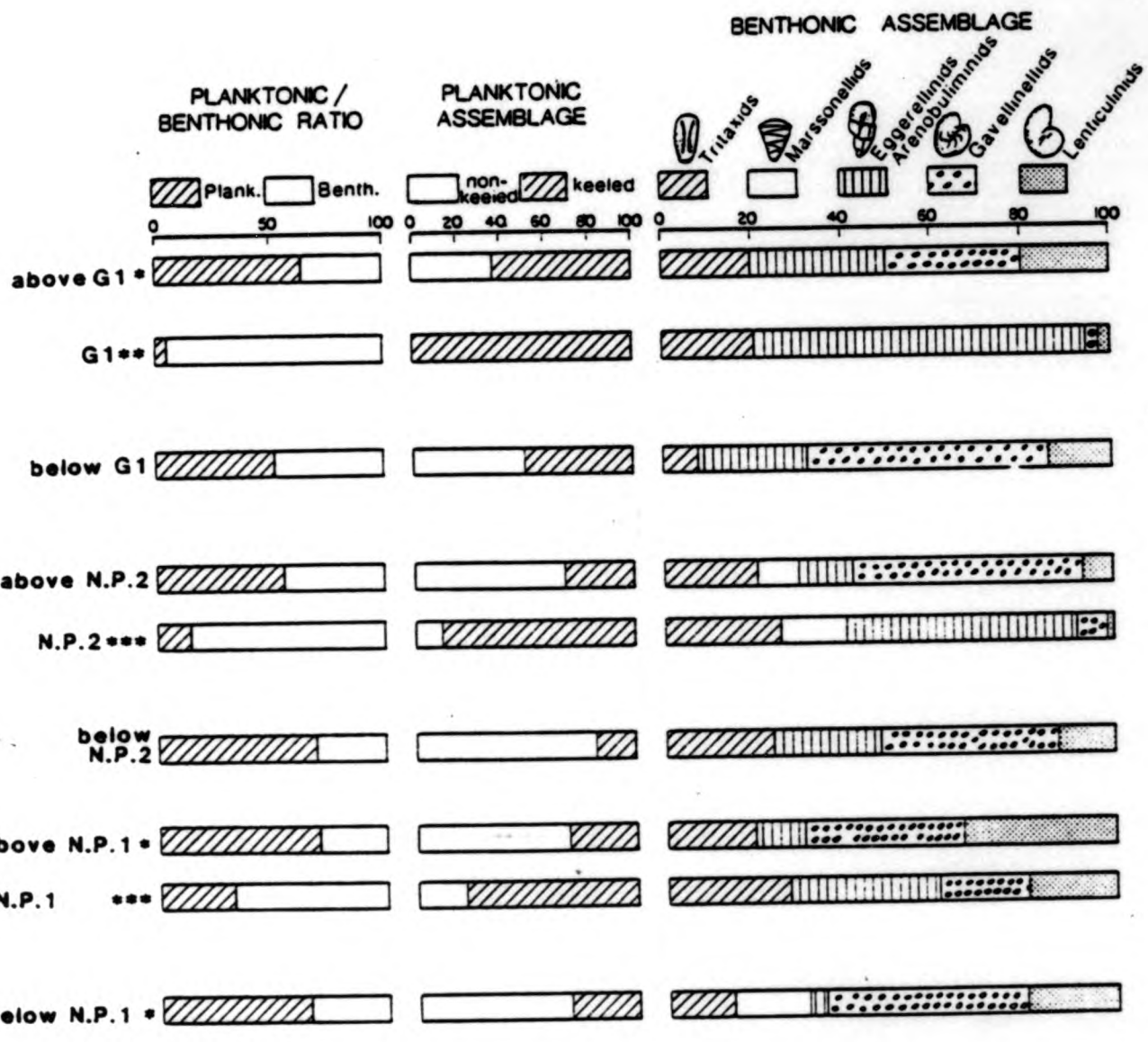

PLANKTONIC / BENTHONIC RATIO
PLANKTONIC ASSEMBLAGE
BENTHONIC ASSEMBLAGE
Trilaxids
Marssonellids
Eggerellinids Arenobuliminids
Gavellinellids
Lenticulinids
Plank.
Benth.
non-keeled
keeled
0 50 100
0 20 40 60 80 100
0 20 40 60 80 100
above G1 *
G1**
below G1
above N.P.2
N.P.2***
below N.P.2
above N.P.1 *
N.P.1 ***
below N.P.1 *

Figure 5.2

DINOFLAGELLATE CYST VARIATIONS ACROSS THREE MIDDLE TURONIAN MARL BANDS

Dinoflagellate cyst data across New Pit Marls 1 and 2, and Glynde Marl 1 from Burghclere. None of the samples were particularly rich (see number counted), and a plot of cysts per gram of sediment shows no consistent variation.

Key:

AG	35 cm above Glynde Marl 1
G	Glynde Marl 1 [Caburn]
BG	30 cm below Glynde Marl 1
ANP2	20 cm above New Pit Marl 2
NP2	New Pit Marl 2
BNP2	10 cm below New Pit Marl 2
ANP1	30 cm above New Pit Marl 1
NP1	New Pit Marl 1
BNP1	20 cm below New Pit Marl 1

Dinoflagellate cyst results, Burghclere

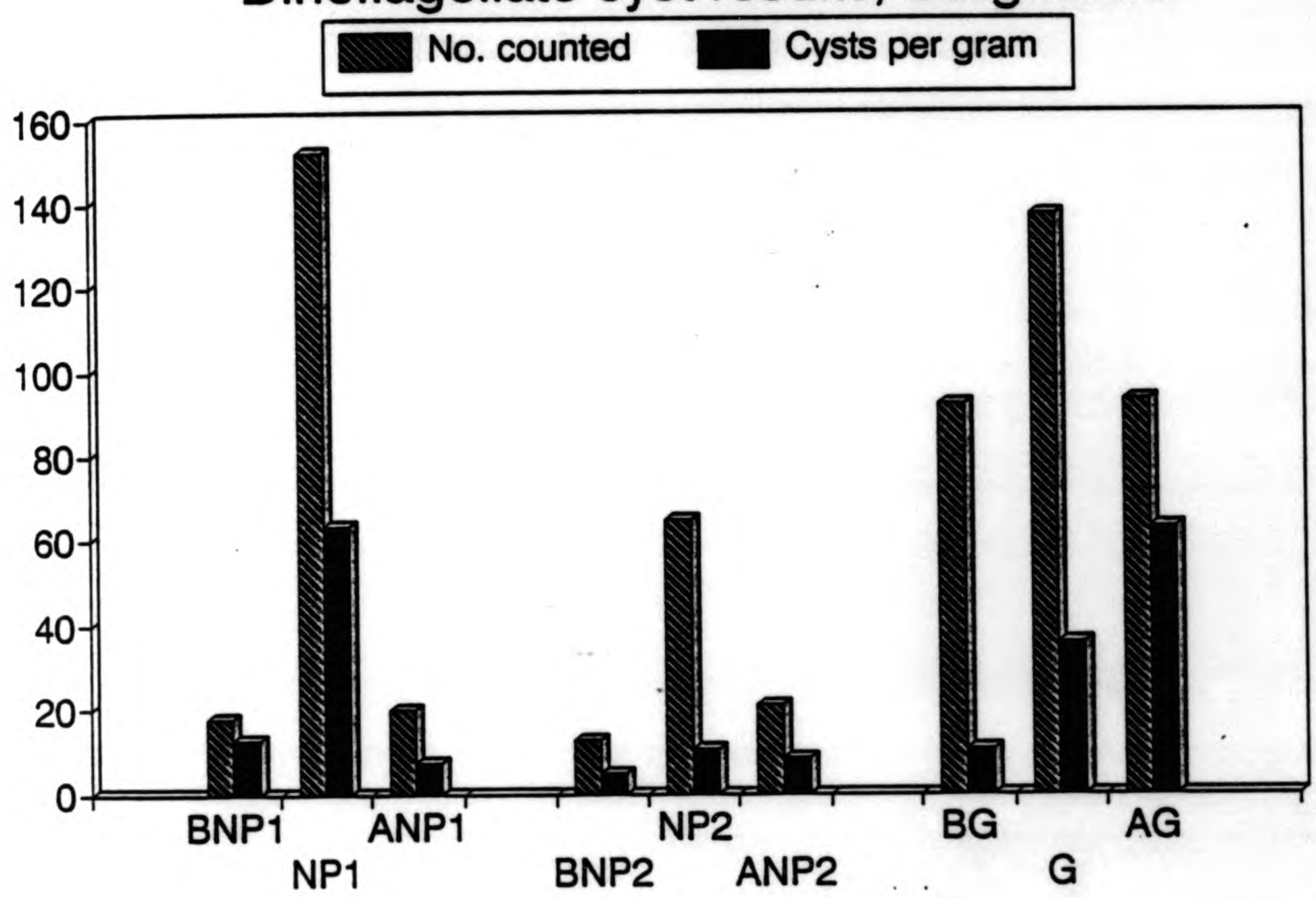


Figure 5.3

CALCAREOUS NANNOFAUNA VARIATIONS ACROSS NEW PIT MARLS 1 AND 2 (BEACHY HEAD).

Key:

K24 60 cm above New Pit 1.

K25 New Pit 1.

K26 45 cm below New Pit 1.

K23 30 cm above New Pit 2

K21c marly chalk 5 cm down from the top of the seam.

K21a marly chalk 10 cm up from the base of the seam.

K21b marly chalk 5 cm up from the base of the seam.

K22 25 cm below New Pit Marl 2.

/ = very rare (0-2%)

X = rare (3-5%)

o = few (6-15%)

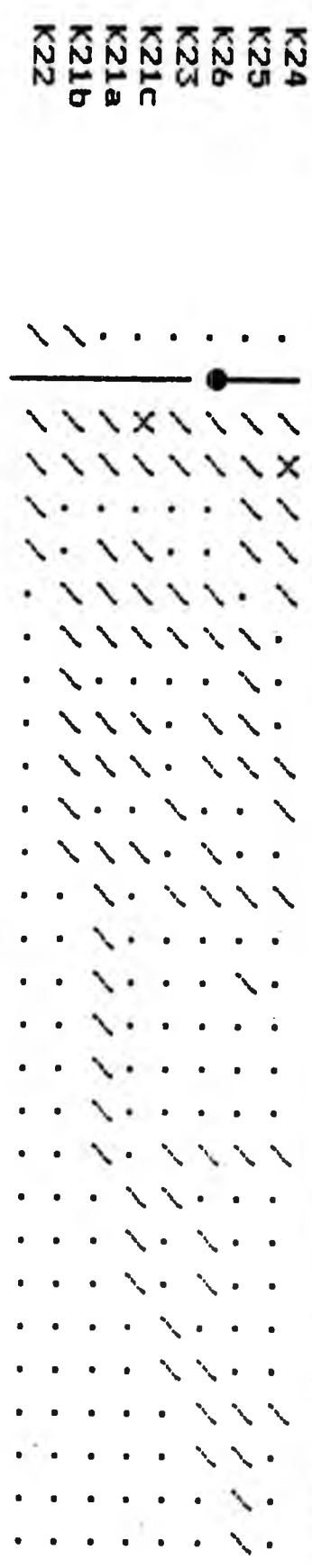
● = common (16-25%)

| = abundant (26-100%)

? = questionably present

. = not present

K24	K25	K26	K23	K21c	K21a	K21b	K22		
\	\	\	·	\	\	\	\	1	Bipodorhabdus brooksii
X	X	X	\	X	O	X	O	2	Biscutum ellipticum
\	\	\	\	·	·	\	·	3	Braarudosphaera bigelowii
\	\	\	\	\	\	\	\	4	Broinsonia enormis
\	\	\	\	\	\	\	\	5	Broinsonia signata
\	\	\	\	\	\	·	\	6	Calculites obscurus
\	\	·	·	\	\	\	\	7	Chiastozygus litterarius
\	\	·	·	·	·	·	\	8	Cretarhabdus striatus
\	·	·	\	\	·	\	\	9	Cyclagelosphaera deflandrei
\	·	·	·	·	\	·	·	10	Cyclagelosphaera margerelii
\	·	·	\	\	\	\	·	11	Cylindralithus coronatus
\	\	\	\	\	X	\	\	12	Discorhabdus ignotus
\	\	\	·	\	\	\	·	13	Eiffellithus eximius
O	X	O	X	O	O	O	X	14	Eiffellithus turriseiffelii
\	X	X	X	\	X	\	\	15	Eprolithus floralis
\	O	O	X	\	X	O	\	16	Eprolithus moratus
O	\	X	X	X	X	\	X	17	Gartnerago nanum
\	\	\	\	\	\	\	\	18	Gartnerago obliquum
\	\	\	\	·	\	\	\	19	Gephyrorhabdus coronadventis
\	·	\	\	\	\	\	\	20	Helicolithus bifarius
X	\	\	\	X	X	\	X	21	Helicolithus trabeculatus
\	\	\	\	\	\	\	\	22	Lithraphidites carniolensis
\	\	\	·	·	\	·	·	23	Manivitella pemmatoidea
\	\	·	·	\	\	\	\	24	Nannoconus sp.
O	O	O	O	O	O	O	O	25	Prediscosphaera cretacea
\	\	\	\	\	·	\	\	26	Quadrum gartneri
\	\	\	\	\	·	\	\	27	Retecapsa angustiforata
\	\	\	\	\	X	\	X	28	Retecapsa crenulata
\	\	\	\	\	\	·	\	29	Rhagodiscus achlyostaurion
\	·	·	·	·	\	\	\	30	Rhagodiscus plebeius
\	·	·	\	\	·	\	\	31	Tranolithus gabalus
\	\	\	·	\	\	\	\	32	Tranolithus minimus
O	\	X	\	O	O	X	O	33	Tranolithus orionatus

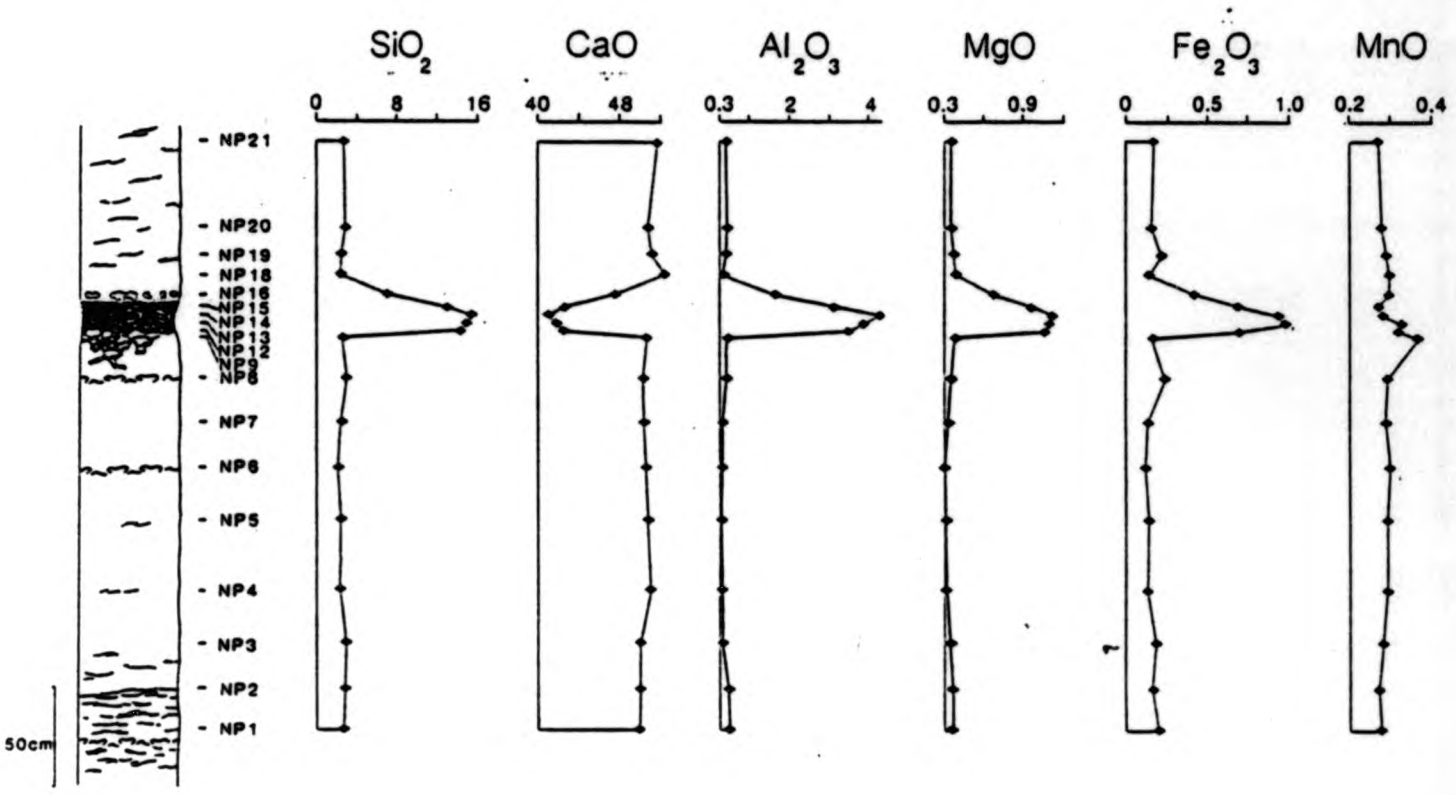


34	Vagalapilla angusta
35	Watznaueria barnesae
36	Watznaueria fossacincta
37	Zeugrhabdotus compactus
38	Zeugrhabdotus elegans
39	Zeugrhabdotus embergeri
40	Biscutum coronum
41	Cribrosphaerella ehrenbergii
42	Cylindralithus biarcus
43	Cylindralithus laffittei
44	Radiolithus planus
45	Rhagodiscus angustus
46	Watznaueria biporta
47	Ahmuellerella octoradiata
48	Corollithion signum
49	Haqius circumradiatus
50	Nannoconus elongatus
51	Prediscosphaera spinosa
52	Staurolithites sp.
53	Zeugrhabdotus erectus
54	Cylindralithus nudus
55	Nannoconus truitti frequens
56	Nannoconus truitti rectangularis
57	Nannoconus multicadus
58	Watznaueria ovata
59	Kamptnerius magnificus
60	Rhagodiscus splendens
61	Rhagodiscus asper
62	Scampanella bispinosa

Figure 6.1

MAJOR ELEMENT TRENDS ACROSS NEW PIT MARL 2, BEACHY HEAD.

All values are in oxide weight percent apart from strontium which is in parts per million.


SiO2
CaO
Al2O3
MgO
Fe2O3
MnO
0 8 16
40 48
0.3 2 4
0.3 0.9
0 0.5 1.0
0.2 0.4
NP21
NP20
NP19
NP18
NP16
NP15
NP14
NP13
NP12
NP9
NP8
NP7
NP6
NP5
NP4
NP3
NP2
NP1
50cm

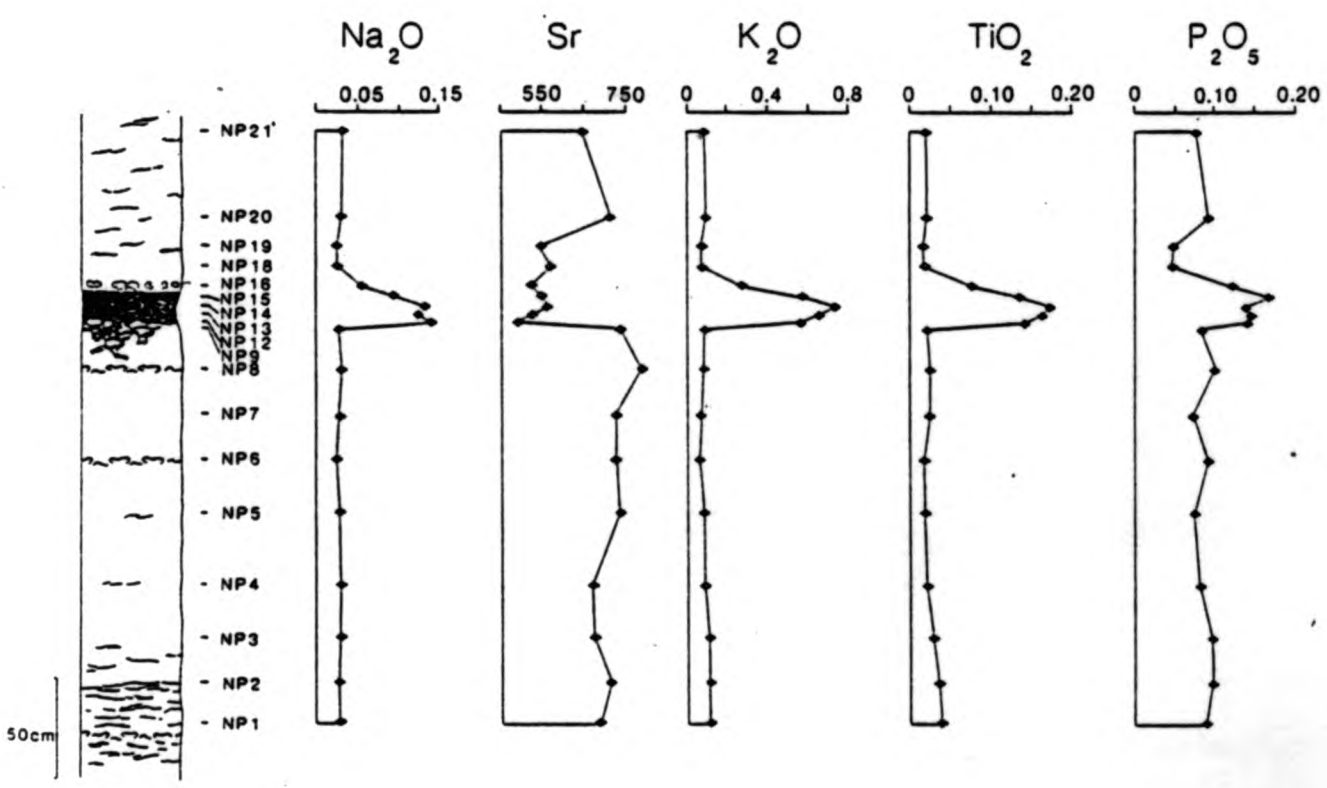
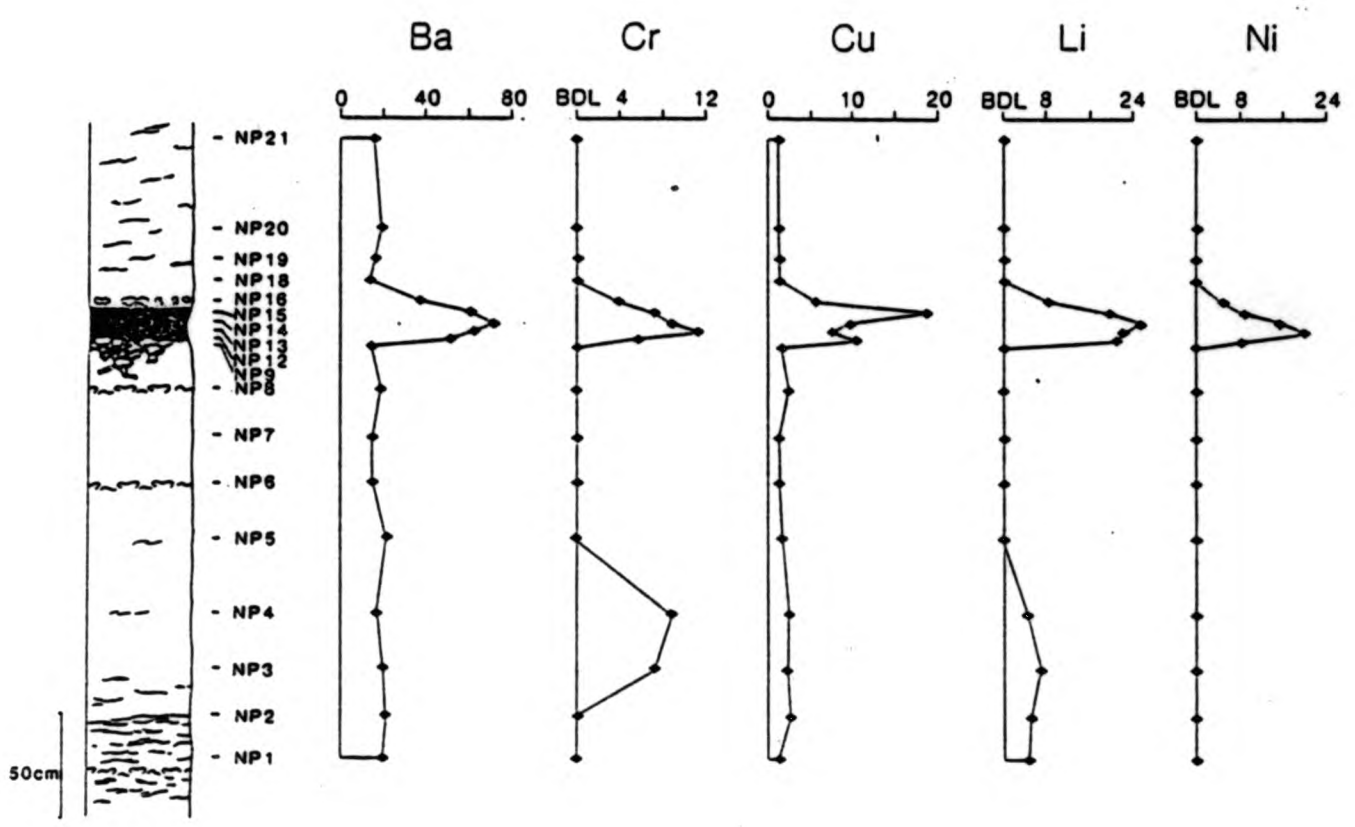

Na2O
Sr
K2O
TiO2
P2O5
0.05 0.15
550 750
0 0.4 0.8
0 0.10 0.20
0 0.10 0.20
NP21
NP20
NP19
NP18
NP16
NP15
NP14
NP13
NP12
NP9
NP8
NP7
NP6
NP5
NP4
NP3
NP2
NP1
50cm

Figure 6.2

TRACE ELEMENT TRENDS ACROSS NEW PIT MARL 2, BEACHY HEAD.

All values are in parts per million; BDL signifies that the element was present in concentrations below the acceptable detection limit of ICP-AES.


Ba
Cr
Cu
Li
Ni
0 40 80
BDL 4 12
0 10 20
BDL 8 24
BDL 8 24
NP21
NP20
NP19
NP18
NP16
NP15
NP14
NP13
NP12
NP9
NP8
NP7
NP6
NP5
NP4
NP3
NP2
NP1
50cm

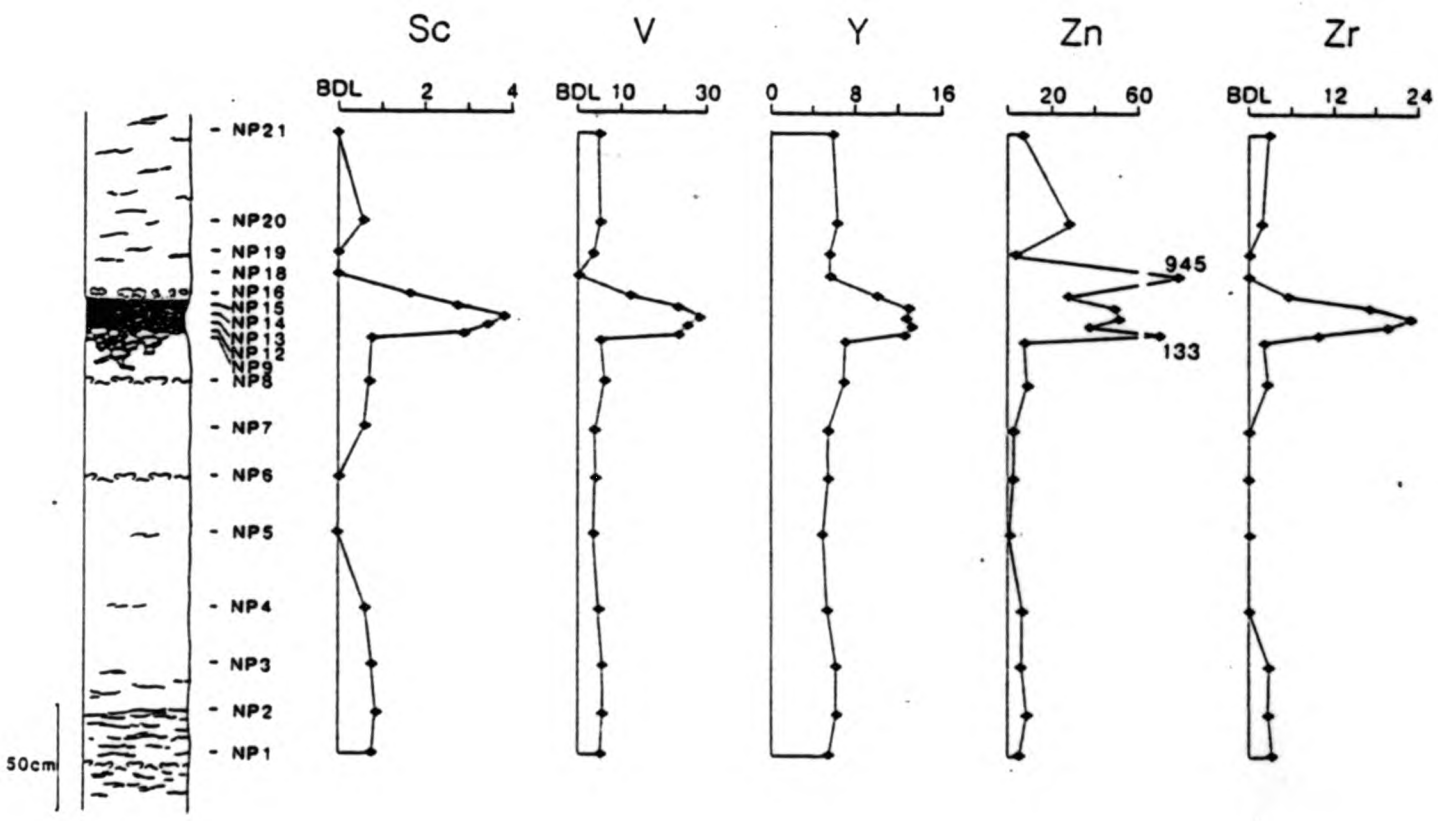

Sc
V
Y
Zn
Zr
BDL 2 4
BDL 10 30
0 8 16
20 60
BDL 12 24
945
133
NP21
NP20
NP19
NP18
NP16
NP15
NP14
NP13
NP12
NP9
NP8
NP7
NP6
NP5
NP4
NP3
NP2
NP1
50cm

Figure 6.3

PEARSONS CORRELATION MATRIX OF MAJOR AND TRACE ELEMENT DATA FROM NEW PIT MARL 2, BEACHY HEAD.

Key: correlation coefficient
(number of samples)
significance level

	SiO2	TiO2	Al2O3	Fe2O3	MnO	MgO	CaO	Na2O	K2O
SiO2	1.0000	0.9943	0.9978	0.9848	0.1349	0.9967	-0.9879	0.9864	0.9953
	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)
	0.0000	0.0000	0.0000	0.0000	0.5936	0.0000	0.0000	0.0000	0.0000
TiO2	0.9943	1.0000	0.9960	0.9868	0.1102	0.9920	-0.9923	0.9750	0.9966
	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)
	0.0000	0.0000	0.0000	0.0000	0.6635	0.0000	0.0000	0.0000	0.0000
Al2O3	0.9978	0.9960	1.0000	0.9894	0.1343	0.9967	-0.9873	0.9833	0.9980
	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)
	0.0000	0.0000	0.0000	0.0000	0.5953	0.0000	0.0000	0.0000	0.0000
Fe2O3	0.9848	0.9868	0.9894	1.0000	0.1471	0.9823	-0.9747	0.9618	0.9884
	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)
	0.0000	0.0000	0.0000	0.0000	0.5604	0.0000	0.0000	0.0000	0.0000
MnO	0.1349	0.1102	0.1343	0.1471	1.0000	0.1521	-0.1192	0.1640	0.1055
	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)
	0.5936	0.6635	0.5953	0.5604	0.0000	0.5469	0.6376	0.5155	0.6769
MgO	0.9967	0.9920	0.9967	0.9823	0.1521	1.0000	-0.9796	0.9840	0.9923
	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)
	0.0000	0.0000	0.0000	0.0000	0.5469	0.0000	0.0000	0.0000	0.0000
CaO	-0.9879	-0.9923	-0.9873	-0.9747	-0.1192	-0.9796	1.0000	-0.9706	-0.9886
	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)
	0.0000	0.0000	0.0000	0.0000	0.6376	0.0000	0.0000	0.0000	0.0000
Na2O	0.9864	0.9750	0.9833	0.9618	0.1640	0.9840	-0.9706	1.0000	0.9733
	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)
	0.0000	0.0000	0.0000	0.0000	0.5155	0.0000	0.0000	0.0000	0.0000
K2O	0.9953	0.9966	0.9980	0.9884	0.1055	0.9923	-0.9886	0.9733	1.0000
	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)
	0.0000	0.0000	0.0000	0.0000	0.6769	0.0000	0.0000	0.0000	0.0000
P2O5	0.8733	0.8807	0.8561	0.8434	0.0268	0.8461	-0.9029	0.8335	0.8688
	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)
	0.0000	0.0000	0.0000	0.0000	0.9158	0.0000	0.0000	0.0000	0.0000
Sr	-0.7141	-0.6913	-0.7068	-0.6972	-0.0790	-0.7492	0.6342	-0.6979	-0.6930
	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)
	0.0009	0.0015	0.0010	0.0013	0.7554	0.0003	0.0047	0.0013	0.0014
Ba	0.9841	0.9883	0.9870	0.9793	0.0505	0.9791	-0.9830	0.9496	0.9936
	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)
	0.0000	0.0000	0.0000	0.0000	0.8421	0.0000	0.0000	0.0000	0.0000
Cr	0.1215	0.1620	0.1623	0.2859	0.0991	0.0812	-0.1527	0.1009	0.1810
	(8)	(8)	(8)	(8)	(8)	(8)	(8)	(8)	(8)
	0.7744	0.7016	0.7010	0.4925	0.8154	0.8484	0.7181	0.8121	0.6679
Cu	0.8508	0.8420	0.8297	0.7946	-0.0667	0.8314	-0.8547	0.7958	0.8464
	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)
	0.0000	0.0000	0.0000	0.0001	0.7926	0.0000	0.0000	0.0001	0.0000
Li	0.9825	0.9838	0.9879	0.9681	0.3844	0.9781	-0.9891	0.9745	0.9869
	(9)	(9)	(9)	(9)	(9)	(9)	(9)	(9)	(9)
	0.0000	0.0000	0.0000	0.0000	0.3071	0.0000	0.0000	0.0000	0.0000
Ni	0.7632	0.8298	0.8164	0.9538	0.3141	0.7685	-0.7555	0.6420	0.8126
	(5)	(5)	(5)	(5)	(5)	(5)	(5)	(5)	(5)
	0.1333	0.0821	0.0918	0.0118	0.6067	0.1289	0.1397	0.2428	0.0946
Sc	0.9930	0.9969	0.9980	0.9917	0.1021	0.9938	-0.9930	0.9698	0.9981
	(13)	(13)	(13)	(13)	(13)	(13)	(13)	(13)	(13)
	0.0000	0.0000	0.0000	0.0000	0.7400	0.0000	0.0000	0.0000	0.0000
V	0.9967	0.9954	0.9969	0.9828	0.1281	0.9948	-0.9914	0.9756	0.9973
	(17)	(17)	(17)	(17)	(17)	(17)	(17)	(17)	(17)
	0.0000	0.0000	0.0000	0.0000	0.6242	0.0000	0.0000	0.0000	0.0000
Y	0.9753	0.9665	0.9659	0.9560	0.1918	0.9715	-0.9625	0.9434	0.9654
	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)
	0.0000	0.0000	0.0000	0.0000	0.4457	0.0000	0.0000	0.0000	0.0000
Zn	-0.0410	-0.0631	-0.0378	-0.0632	0.0830	-0.0041	0.1248	-0.0356	-0.0517
	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)	(18)
	0.8717	0.8035	0.8818	0.8033	0.7433	0.9873	0.6216	0.8884	0.8386
Zr	0.9315	0.9506	0.9473	0.9622	0.0281	0.9252	-0.9394	0.8757	0.9622
	(12)	(12)	(12)	(12)	(12)	(12)	(12)	(12)	(12)
	0.0000	0.0000	0.0000	0.0000	0.9309	0.0000	0.0000	0.0002	0.0000

correlation coefficient (number of samples) significance level

	Na2O	K2O	P2O5	Sr	Ba	Cr	Cu	Li	Ni	Sc	V	Y	Zn	Zr
9	0.9864	0.9953	0.8733	-0.7141	0.9841	0.1215	0.8508	0.9825	0.7632	0.9930	0.9967	0.9753	-0.0410	0.9315
8)	<18>	<18>	<18>	<18>	<18>	<8>	<18>	<9>	<5>	<13>	<17>	<18>	<18>	<12>
0	0.0000	0.0000	0.0000	0.0009	0.0000	0.7744	0.0000	0.0000	0.1333	0.0000	0.0000	0.0000	0.8717	0.0000
3	0.9750	0.9966	0.8807	-0.6913	0.9883	0.1620	0.8420	0.9838	0.8298	0.9969	0.9954	0.9665	-0.0631	0.9506
8)	<18>	<18>	<18>	<18>	<18>	<8>	<18>	<9>	<5>	<13>	<17>	<18>	<18>	<12>
0	0.0000	0.0000	0.0000	0.0015	0.0000	0.7016	0.0000	0.0000	0.0821	0.0000	0.0000	0.0000	0.8035	0.0000
3	0.9833	0.9980	0.8561	-0.7068	0.9870	0.1623	0.8297	0.9879	0.8164	0.9980	0.9969	0.9659	-0.0378	0.9473
8)	<18>	<18>	<18>	<18>	<18>	<8>	<18>	<9>	<5>	<13>	<17>	<18>	<18>	<12>
0	0.0000	0.0000	0.0000	0.0010	0.0000	0.7010	0.0000	0.0000	0.0918	0.0000	0.0000	0.0000	0.8818	0.0000
7	0.9618	0.9884	0.8434	-0.6972	0.9793	0.2859	0.7946	0.9681	0.9538	0.9917	0.9828	0.9560	-0.0632	0.9622
8)	<18>	<18>	<18>	<18>	<18>	<8>	<18>	<9>	<5>	<13>	<17>	<18>	<18>	<12>
0	0.0000	0.0000	0.0000	0.0013	0.0000	0.4925	0.0001	0.0000	0.0118	0.0000	0.0000	0.0000	0.8033	0.0000
2	0.1640	0.1055	0.0268	-0.0790	0.0505	0.0991	-0.0667	0.3844	0.3141	0.1021	0.1281	0.1918	0.0830	0.0281
8)	<18>	<18>	<18>	<18>	<18>	<8>	<18>	<9>	<5>	<13>	<17>	<18>	<18>	<12>
6	0.5155	0.6769	0.9158	0.7554	0.8421	0.8154	0.7926	0.3071	0.6067	0.7400	0.6242	0.4457	0.7433	0.9309
6	0.9840	0.9923	0.8461	-0.7492	0.9791	0.0812	0.8314	0.9781	0.7685	0.9938	0.9948	0.9713	-0.0041	0.9252
8)	<18>	<18>	<18>	<18>	<18>	<8>	<18>	<9>	<5>	<13>	<17>	<18>	<18>	<12>
0	0.0000	0.0000	0.0000	0.0003	0.0000	0.8484	0.0000	0.0000	0.1289	0.0000	0.0000	0.0000	0.9873	0.0000
0	-0.9706	-0.9886	-0.9029	0.6342	-0.9830	-0.1527	-0.8547	-0.9891	-0.7555	-0.9930	-0.9914	-0.9625	0.1248	-0.9394
8)	<18>	<18>	<18>	<18>	<18>	<8>	<18>	<9>	<5>	<13>	<17>	<18>	<18>	<12>
0	0.0000	0.0000	0.0000	0.0047	0.0000	0.7181	0.0000	0.0000	0.1397	0.0000	0.0000	0.0000	0.6216	0.0000
6	1.0000	0.9733	0.8335	-0.6979	0.9496	0.1009	0.7958	0.9745	0.6420	0.9698	0.9756	0.9434	-0.0356	0.8757
8)	<18>	<18>	<18>	<18>	<18>	<8>	<18>	<9>	<5>	<13>	<17>	<18>	<18>	<12>
0	0.0000	0.0000	0.0000	0.0015	0.0000	0.8121	0.0001	0.0000	0.2428	0.0000	0.0000	0.0000	0.8884	0.0002
5	0.9733	1.0000	0.8688	-0.6930	0.9936	0.1810	0.8464	0.9869	0.8126	0.9981	0.9973	0.9654	-0.0517	0.9622
8)	<18>	<18>	<18>	<18>	<18>	<8>	<18>	<9>	<5>	<13>	<17>	<18>	<18>	<12>
0	0.0000	0.0000	0.0000	0.0014	0.0000	0.6679	0.0000	0.0000	0.0946	0.0000	0.0000	0.0000	0.8386	0.0000
3	0.8335	0.8688	1.0000	-0.4530	0.8852	0.0019	0.8728	0.8603	0.2372	0.9019	0.9015	0.9107	-0.2954	0.8549
8)	<18>	<18>	<18>	<18>	<18>	<8>	<18>	<9>	<5>	<13>	<17>	<18>	<18>	<12>
0	0.0000	0.0000	0.0000	0.0590	0.0000	0.9964	0.0000	0.0029	0.7009	0.0000	0.0000	0.0000	0.2340	0.0004
2	-0.6979	-0.6930	-0.4530	1.0000	-0.6712	0.2880	-0.6124	-0.7494	0.2922	-0.8366	-0.7512	-0.7011	-0.2865	-0.6915
8)	<18>	<18>	<18>	<18>	<18>	<8>	<18>	<9>	<5>	<13>	<17>	<18>	<18>	<12>
7	0.0013	0.0014	0.0590	0.0000	0.0023	0.4891	0.0069	0.0201	0.6333	0.0004	0.0005	0.0012	0.2490	0.0127
0	0.9496	0.9936	0.8852	-0.6712	1.0000	0.1630	0.8625	0.9686	0.7690	0.9914	0.9898	0.9602	-0.0821	0.9689
3)	<18>	<18>	<18>	<18>	<18>	<8>	<18>	<9>	<5>	<13>	<17>	<18>	<18>	<12>
0	0.0000	0.0000	0.0000	0.0023	0.0000	0.6998	0.0000	0.0000	0.1286	0.0000	0.0000	0.0000	0.7461	0.0000
7	0.1009	0.1810	0.0019	0.2880	0.1630	1.0000	-0.1185	0.2950	0.3569	0.1846	0.1288	0.0009	-0.3393	0.5122
8)	<8>	<8>	<8>	<8>	<8>	<8>	<8>	<7>	<5>	<8>	<8>	<8>	<8>	<7>
1	0.8121	0.6679	0.9964	0.4891	0.6998	0.0000	0.7799	0.5206	0.0107	0.6617	0.7611	0.9983	0.4110	0.2399
7	0.7958	0.8464	0.8728	-0.6124	0.8625	-0.1185	1.0000	0.7356	-0.1666	0.7980	0.8574	0.8779	-0.0466	0.7658
8)	<18>	<18>	<18>	<18>	<18>	<8>	<18>	<9>	<5>	<13>	<17>	<18>	<18>	<12>
0	0.0001	0.0000	0.0000	0.0069	0.0000	0.7799	0.0000	0.0239	0.7889	0.0011	0.0000	0.0000	0.8544	0.0037
1	0.9745	0.9869	0.8603	-0.7494	0.9686	0.2950	0.7356	1.0000	0.7392	0.9838	0.9853	0.9275	0.7141	0.9244
3)	<9>	<9>	<9>	<9>	<9>	<7>	<9>	<9>	<5>	<9>	<9>	<9>	<9>	<8>
0	0.0000	0.0000	0.0029	0.0201	0.0000	0.5206	0.0239	0.0000	0.1535	0.0000	0.0000	0.0003	0.0307	0.0010
5	0.6420	0.8126	0.2372	0.2922	0.7690	0.9569	-0.1666	0.7392	1.0000	0.8576	0.7405	0.6713	-0.1450	0.8197
5)	<5>	<5>	<5>	<5>	<5>	<5>	<5>	<5>	<5>	<5>	<5>	<5>	<5>	<5>
7	0.2428	0.0946	0.7009	0.6333	0.1286	0.0107	0.7889	0.1535	0.0000	0.0631	0.1523	0.2147	0.8160	0.0894
0	0.9698	0.9981	0.9019	-0.8566	0.9914	0.1846	0.7980	0.9838	0.8576	1.0000	0.9961	0.9634	0.6979	0.9588
5)	<13>	<13>	<13>	<13>	<13>	<8>	<13>	<9>	<5>	<13>	<13>	<13>	<13>	<11>
0	0.0000	0.0000	0.0000	0.0004	0.0000	0.6617	0.0011	0.0000	0.0631	0.0000	0.0000	0.0000	0.0080	0.0000
4	0.9756	0.9973	0.9015	-0.7512	0.9898	0.1288	0.8574	0.9853	0.7405	0.9961	1.0000	0.9759	0.7682	0.9489
7)	<17>	<17>	<17>	<17>	<17>	<8>	<17>	<9>	<5>	<13>	<17>	<17>	<17>	<12>
0	0.0000	0.0000	0.0000	0.0005	0.0000	0.7611	0.0000	0.0000	0.1523	0.0000	0.0000	0.0000	0.0003	0.0000
5	0.9434	0.9654	0.9107	-0.7011	0.9602	0.0009	0.8779	0.9275	0.6713	0.9634	0.9759	1.0000	-0.0581	0.8945
9)	<18>	<18>	<18>	<18>	<18>	<8>	<18>	<9>	<5>	<13>	<17>	<18>	<18>	<12>
0	0.0000	0.0000	0.0000	0.0012	0.0000	0.9983	0.0000	0.0003	0.2147	0.0000	0.0000	0.0000	0.8190	0.0001
9	-0.0356	-0.0517	-0.2954	-0.2865	-0.0821	-0.3393	-0.0466	0.7141	-0.1450	0.6979	0.7682	-0.0581	1.0000	0.4864
8)	<18>	<18>	<18>	<18>	<18>	<8>	<18>	<9>	<5>	<13>	<17>	<18>	<18>	<12>
5	0.8884	0.8386	0.2340	0.2490	0.7461	0.4110	0.8544	0.0307	0.8160	0.0080	0.0003	0.8190	0.0000	0.1088
4	0.8757	0.9622	0.8549	-0.6915	0.9689	0.5122	0.7658	0.9244	0.8197	0.9588	0.9489	0.8945	0.4864	1.0000
2)	<12>	<12>	<12>	<12>	<12>	<7>	<12>	<8>	<5>	<11>	<12>	<12>	<12>	<12>
0	0.0002	0.0000	0.0004	0.0127	0.0000	0.2399	0.0037	0.0010	0.0894	0.0000	0.0000	0.0001	0.1088	0.0000

:ance level

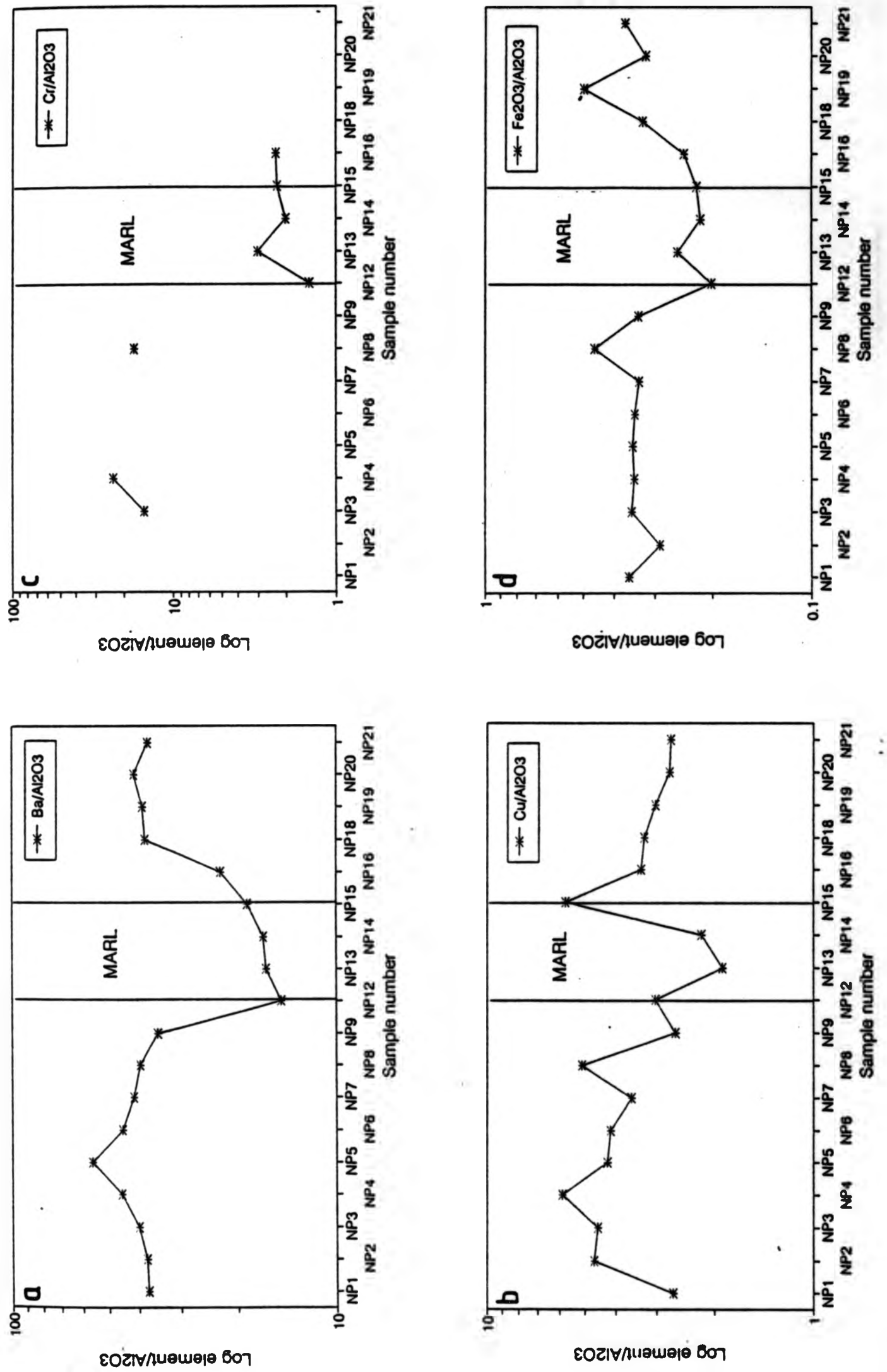
Figure 6.4

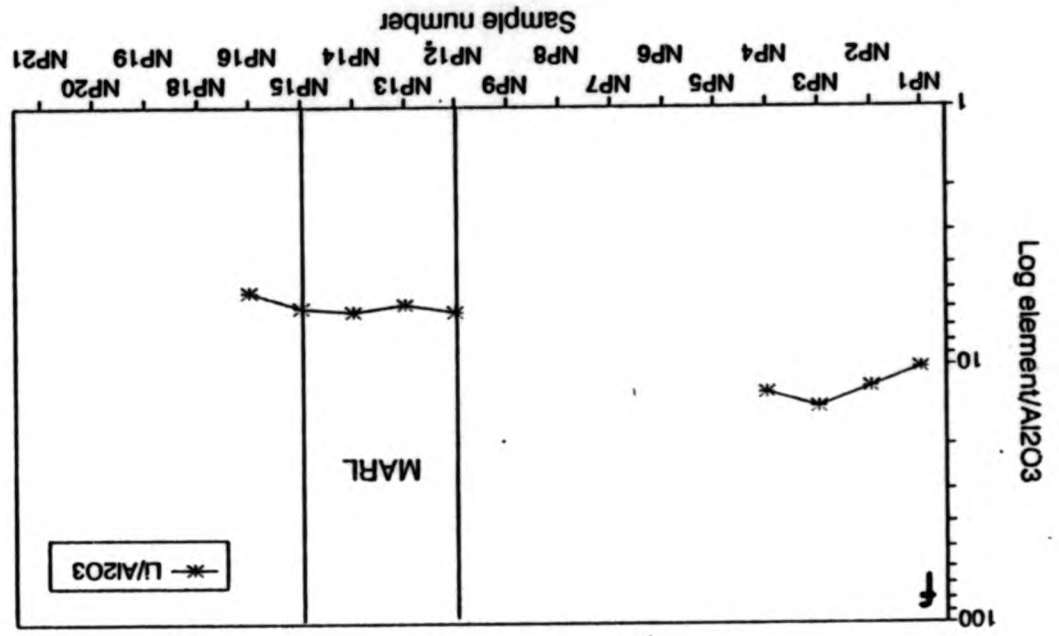
ALUMINIUM NORMALIZED RESULTS ACROSS NEW PIT MARL 2, BEACHY HEAD.

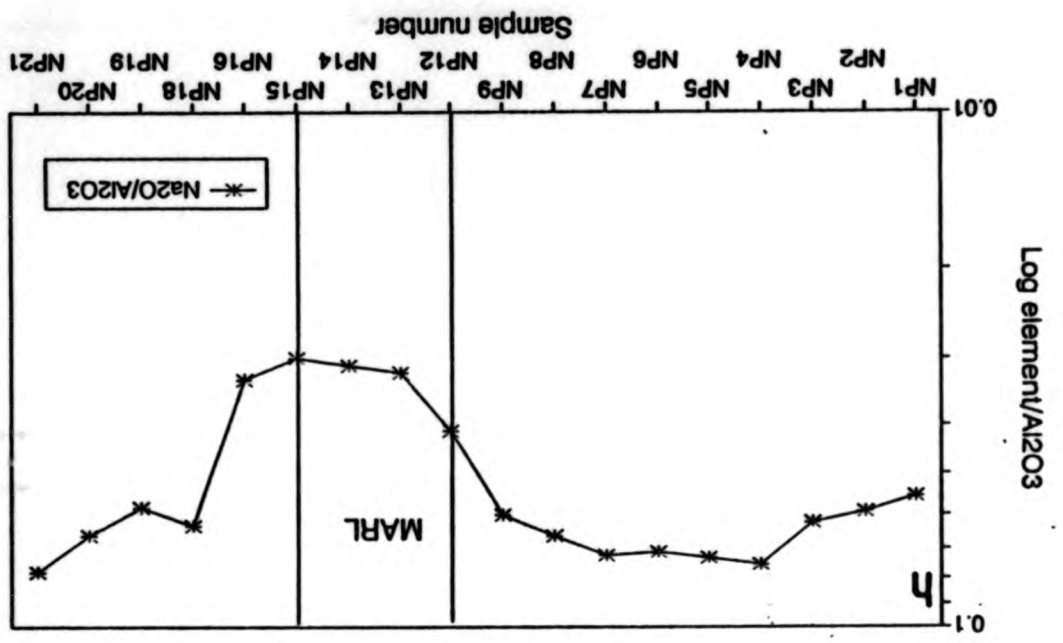
a. Barium.
b. Copper.
c. Chromium.
d. Iron.
e. Potassium.
f. Lithium.
g. Magnesium.
h. Sodium.
i. Nickel.
j. Phosphorous.
k. Scandium.
l. Silica.
m. Strontium.
n. Titanium.
o. Vanadium.
p. Yttrium.
q. Zinc.
r. Zirconium.

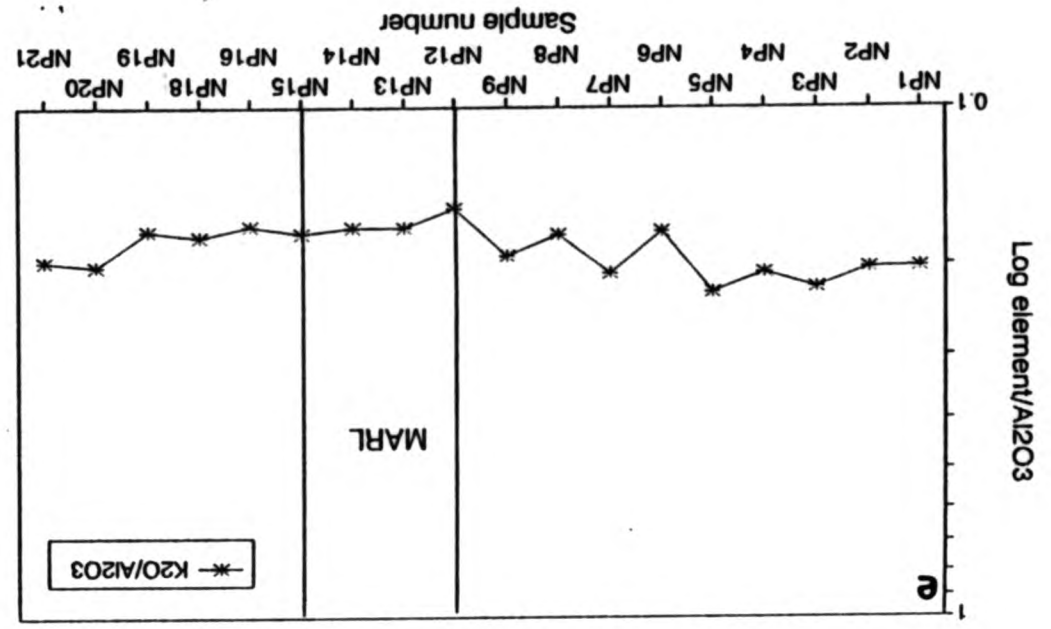
PLEASE NOTE THAT SAMPLE POSITIONS NOT TO SCALE, AND THAT ALL VERTICAL SCALES ARE LOGARITHMIC.

Figure 6.4 cont.









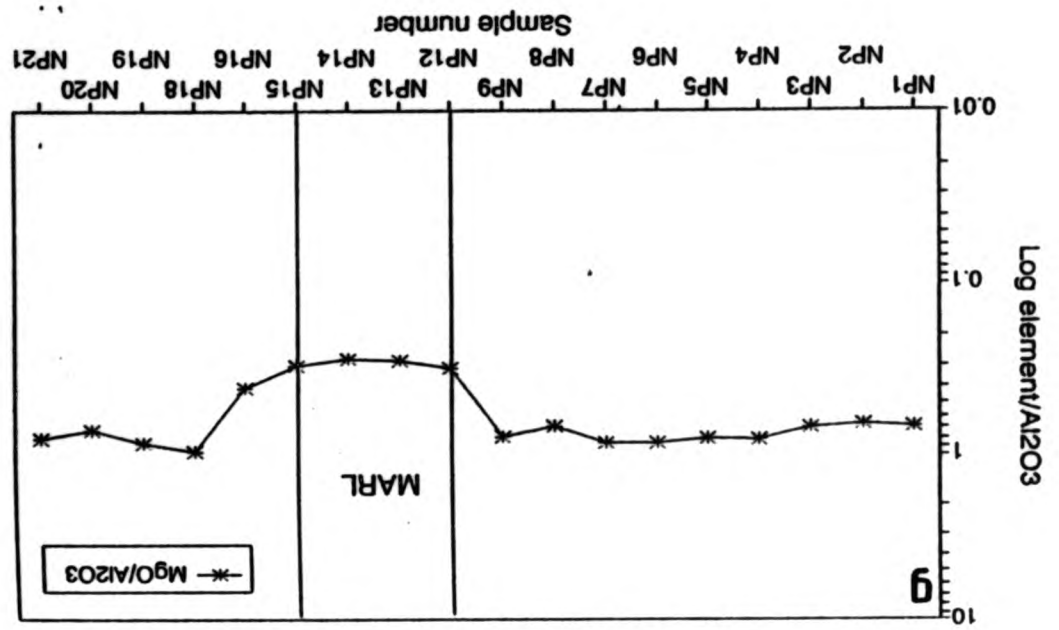
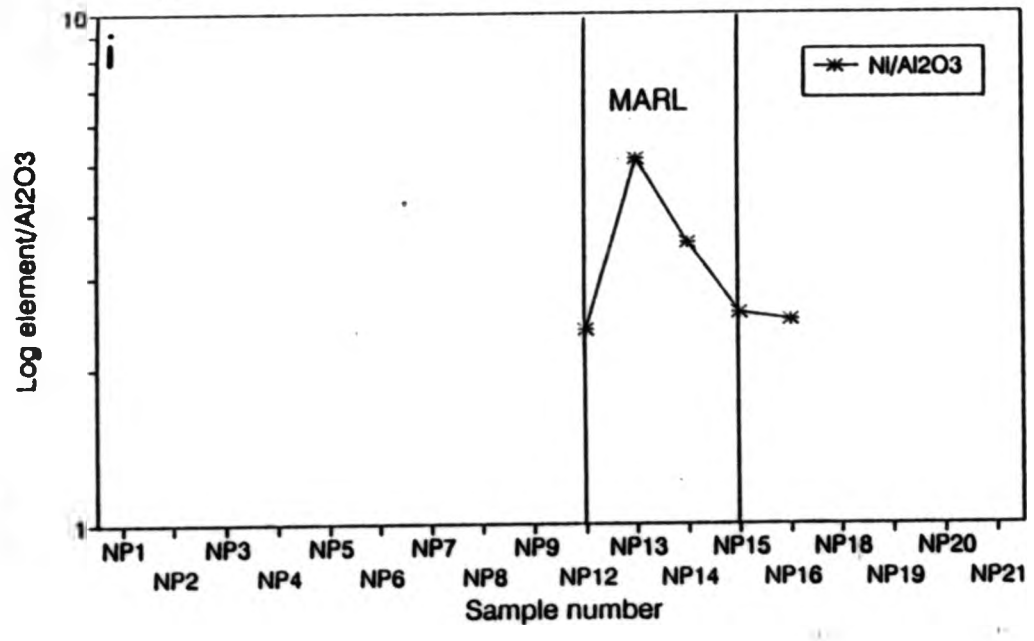
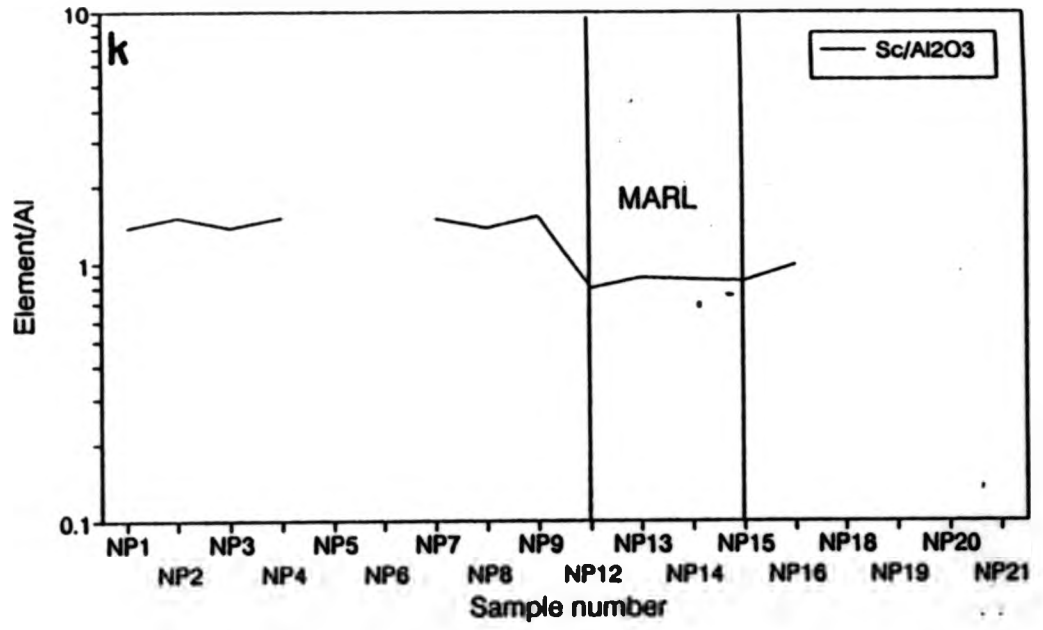
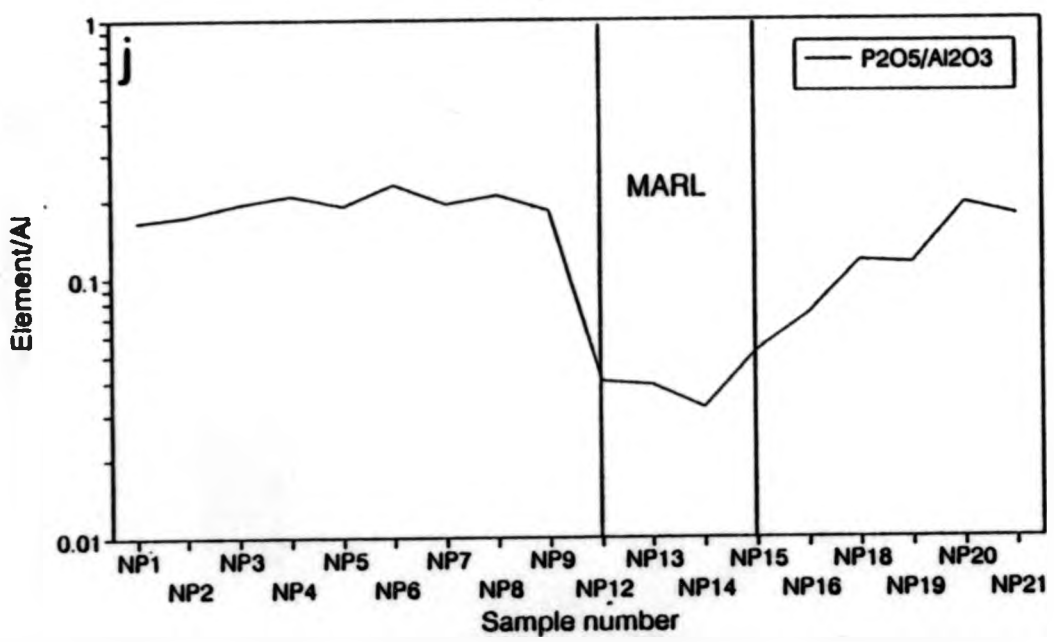


Figure 6.4 cont.







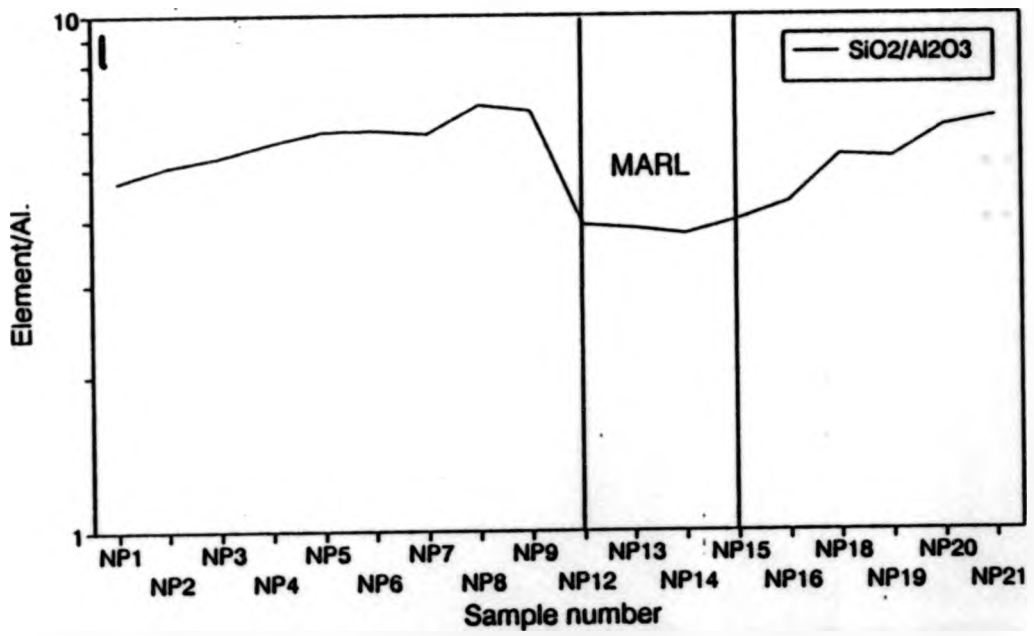
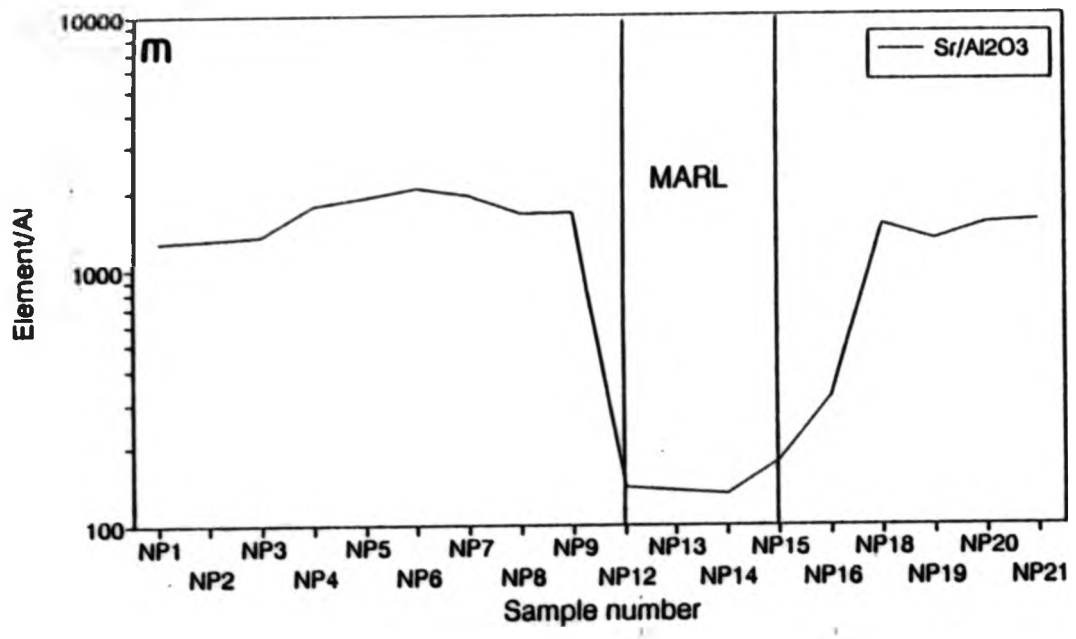
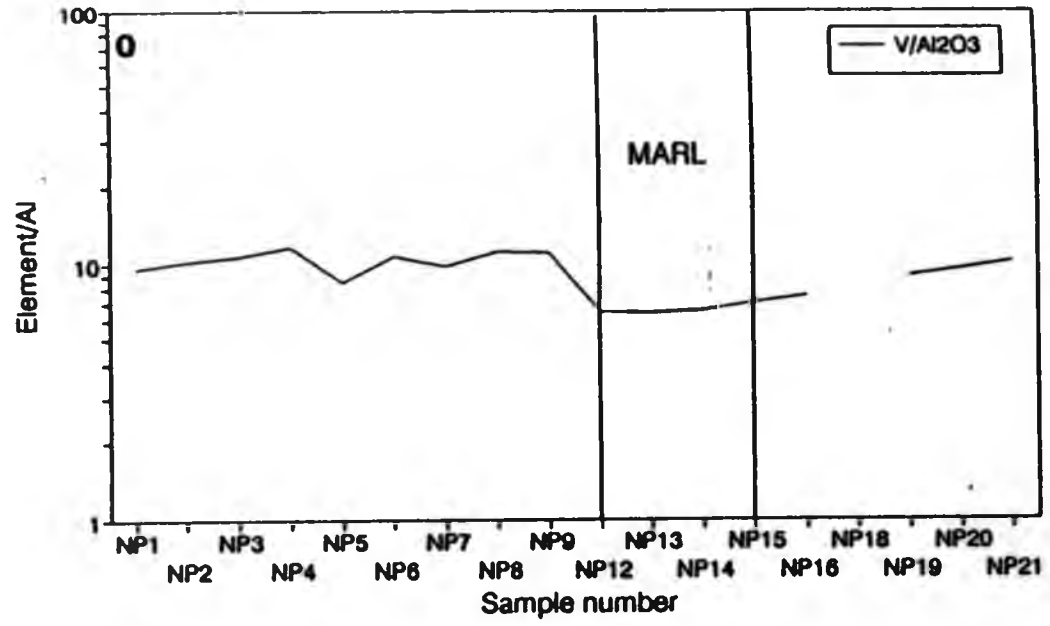
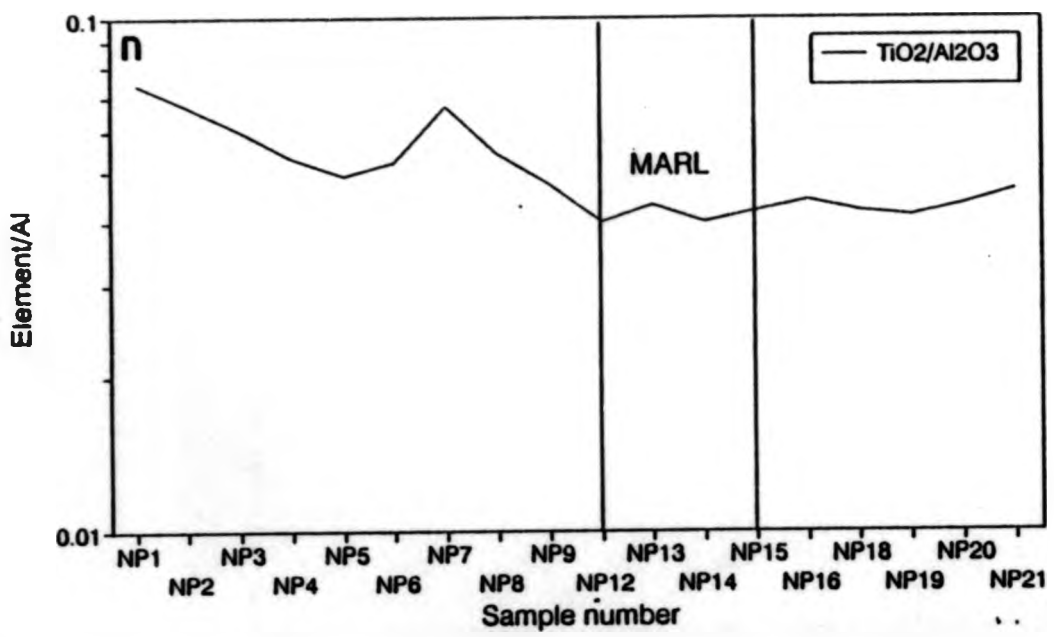


Figure 6.4 cont.







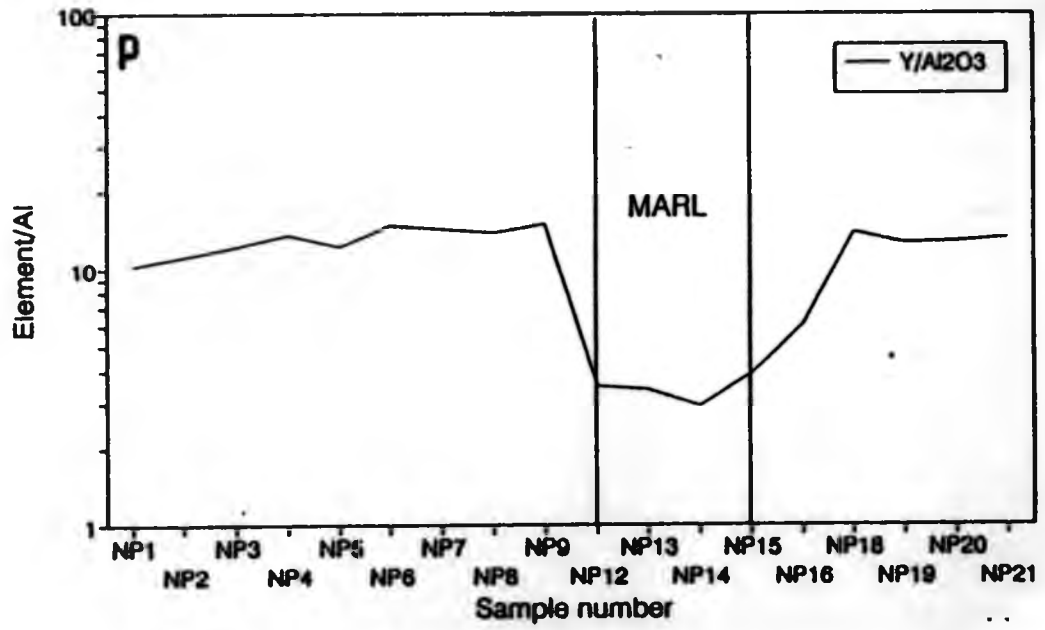


Figure 6.4 cont.

Figure 6.4 cont.

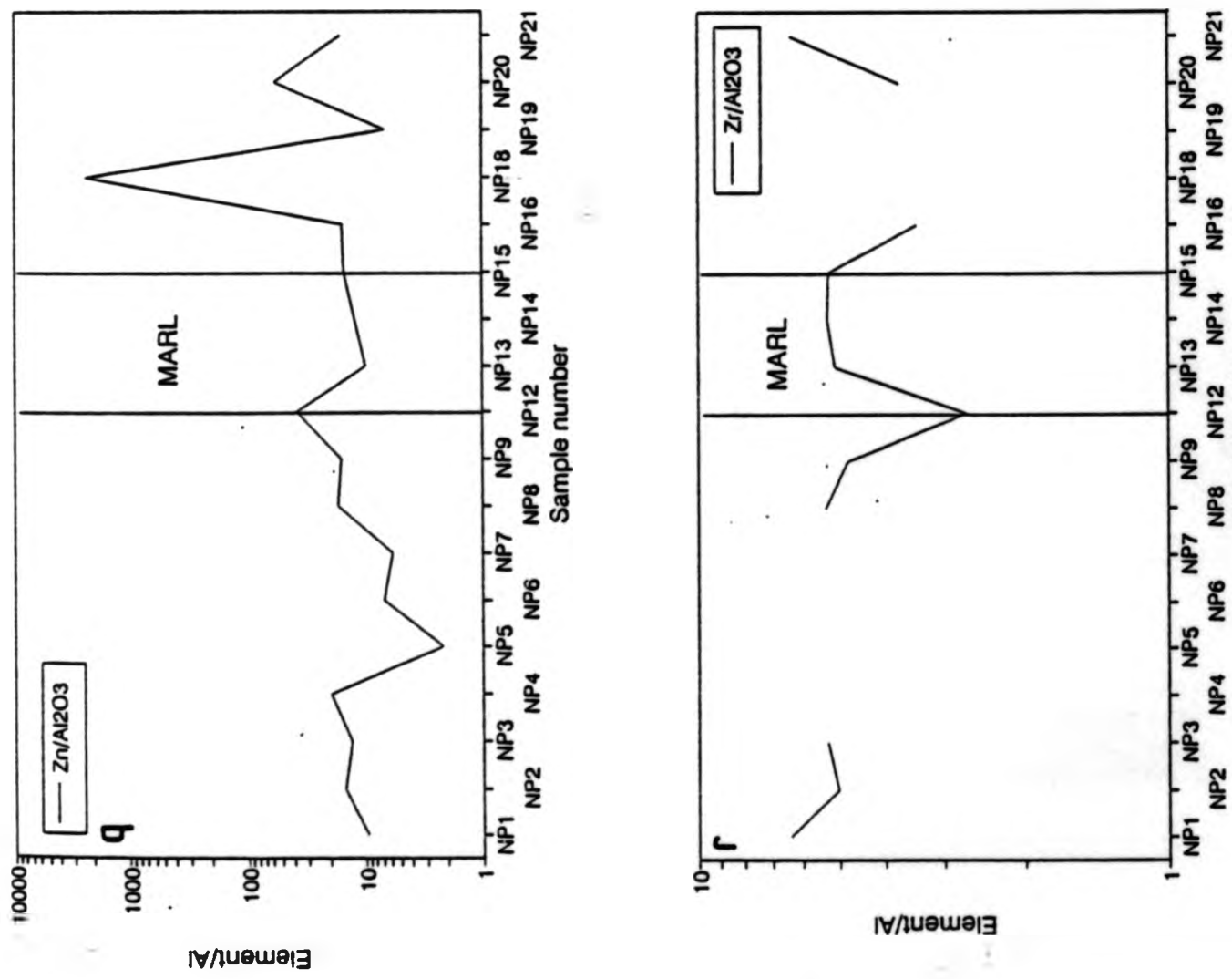
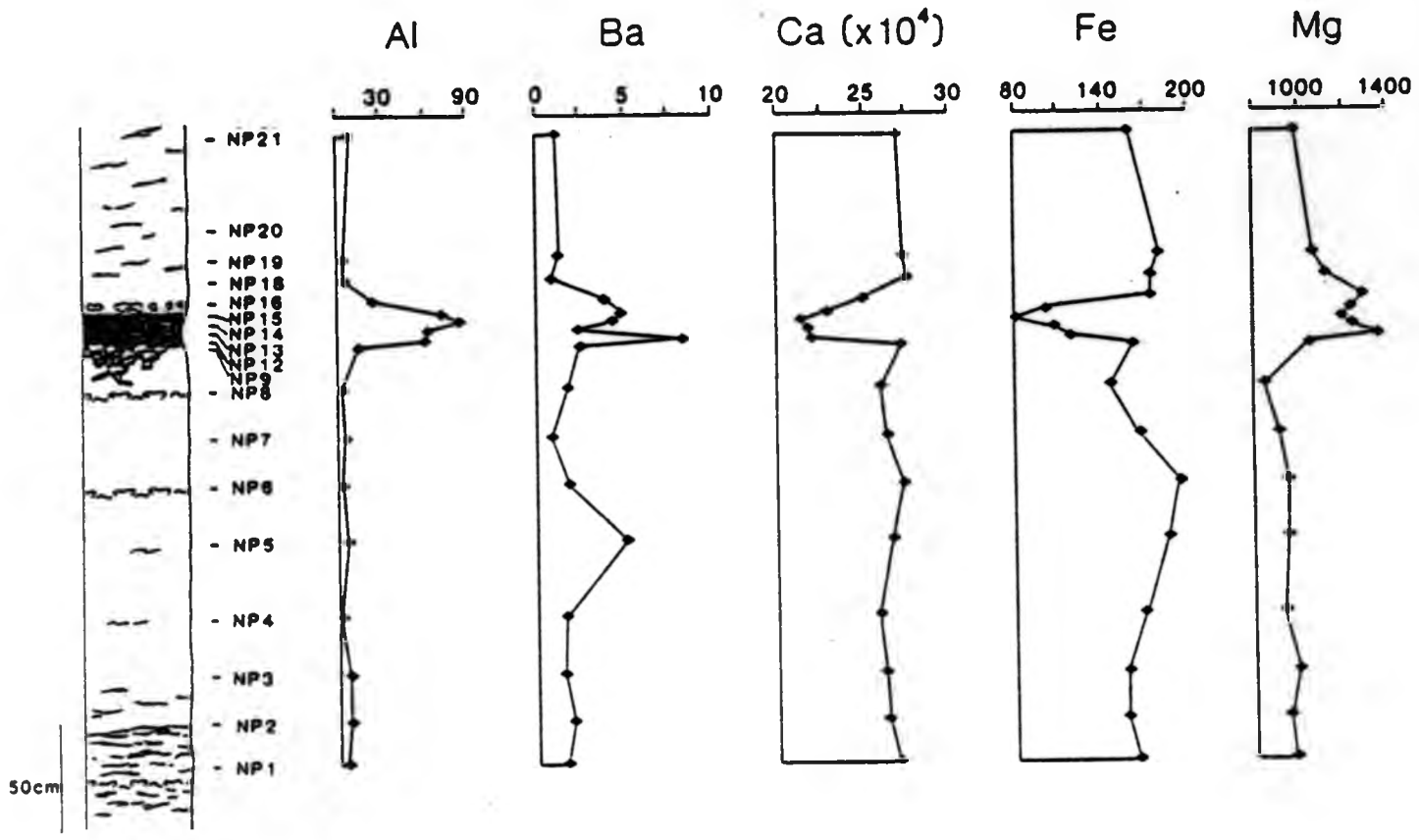


Figure 6.5

CARBONATE ASSOCIATED ELEMENT TRENDS ACROSS NEW PIT MARL 2.

Plots of acetic acid leached (carbonate associated) elements across New Pit Marl 2 at Beachy Head (in parts per million).


Al
Ba
Ca (x10⁴)
Fe
Mg
30 90
0 5 10
20 25 30
80 140 200
1000 1400
NP21
NP20
NP19
NP18
NP16
NP15
NP14
NP13
NP12
NP9
NP8
NP7
NP6
NP5
NP4
NP3
NP2
NP1
50cm

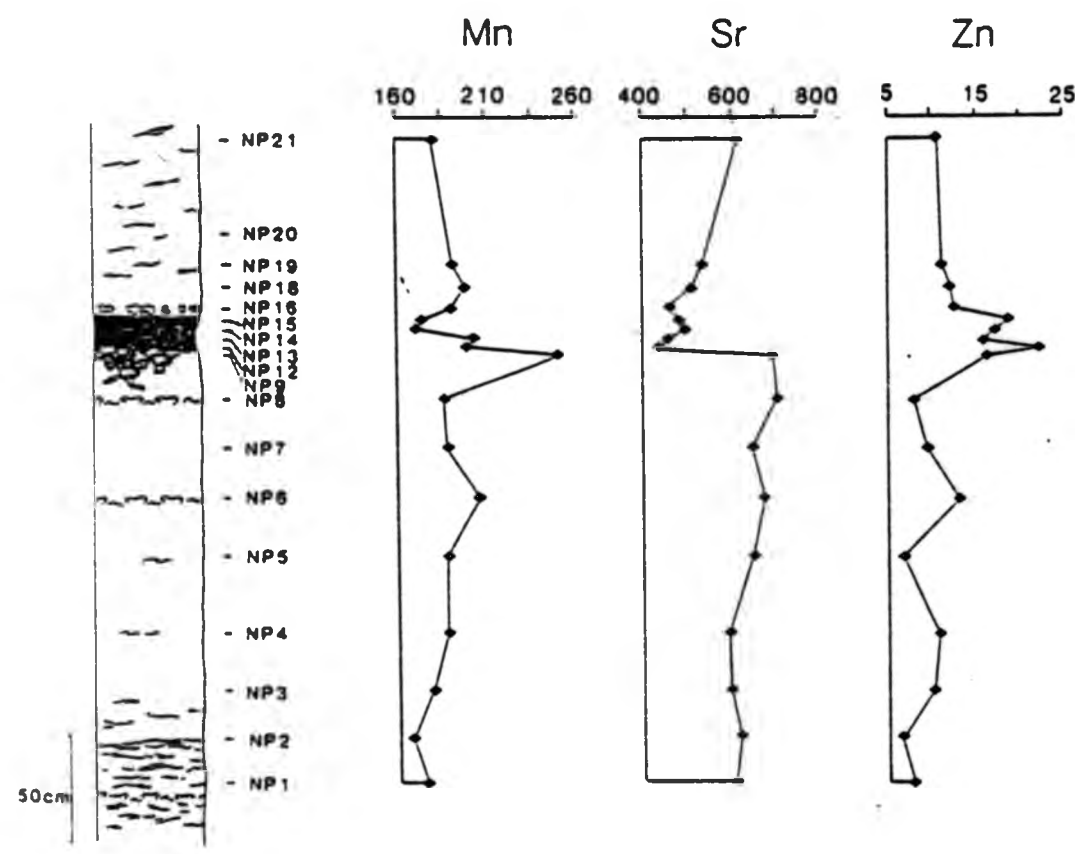

Mn
Sr
Zn
150 210 260
400 600 800
5 15 25
NP21
NP20
NP19
NP18
NP16
NP15
NP14
NP13
NP12
NP9
NP8
NP7
NP6
NP5
NP4
NP3
NP2
NP1
50cm

Figure 6.6

CALCIUM NORMALISED PLOTS OF CARBONATE ASSOCIATED ELEMENTS ACROSS NEW PIT MARL 2. BEACHY HEAD.

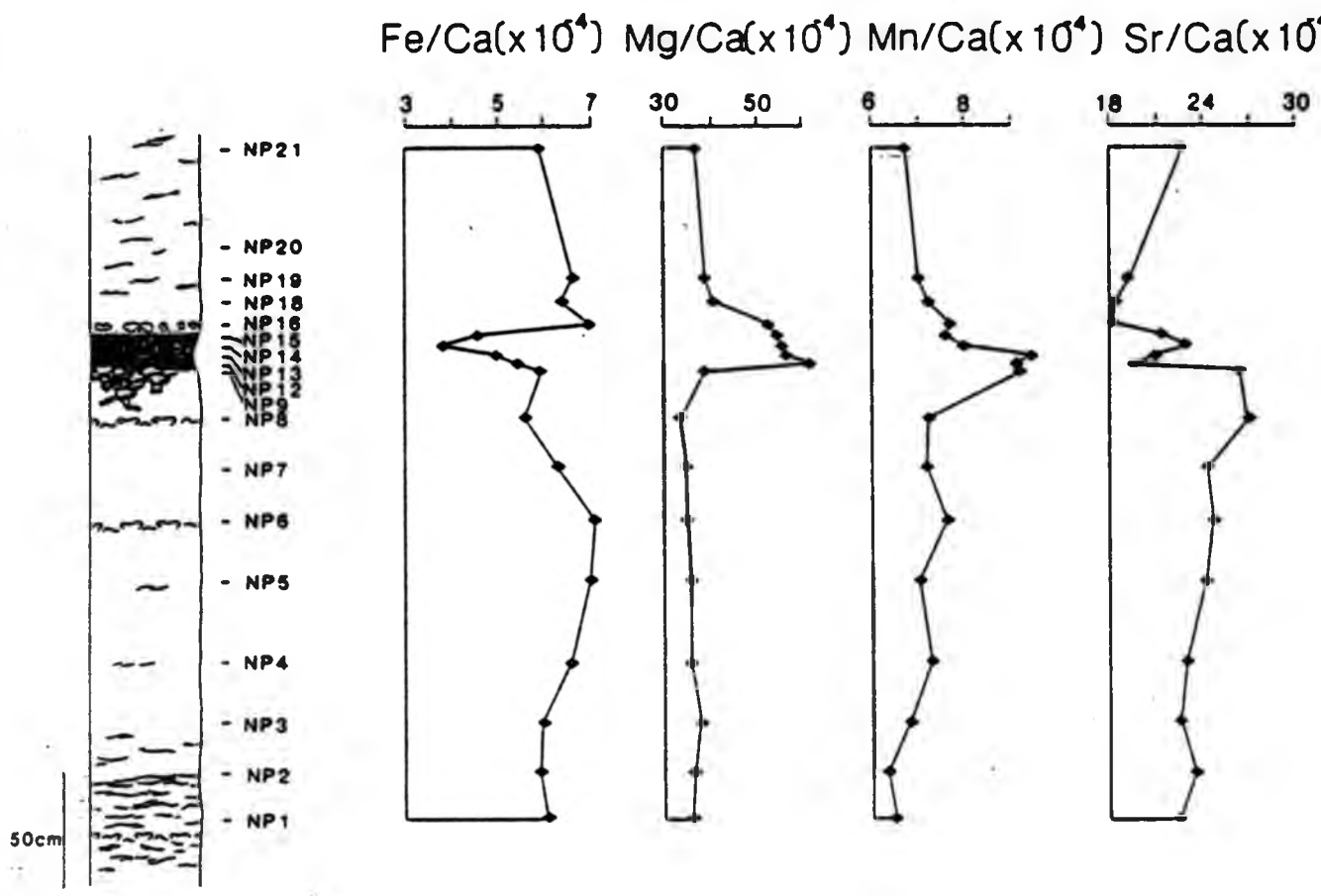


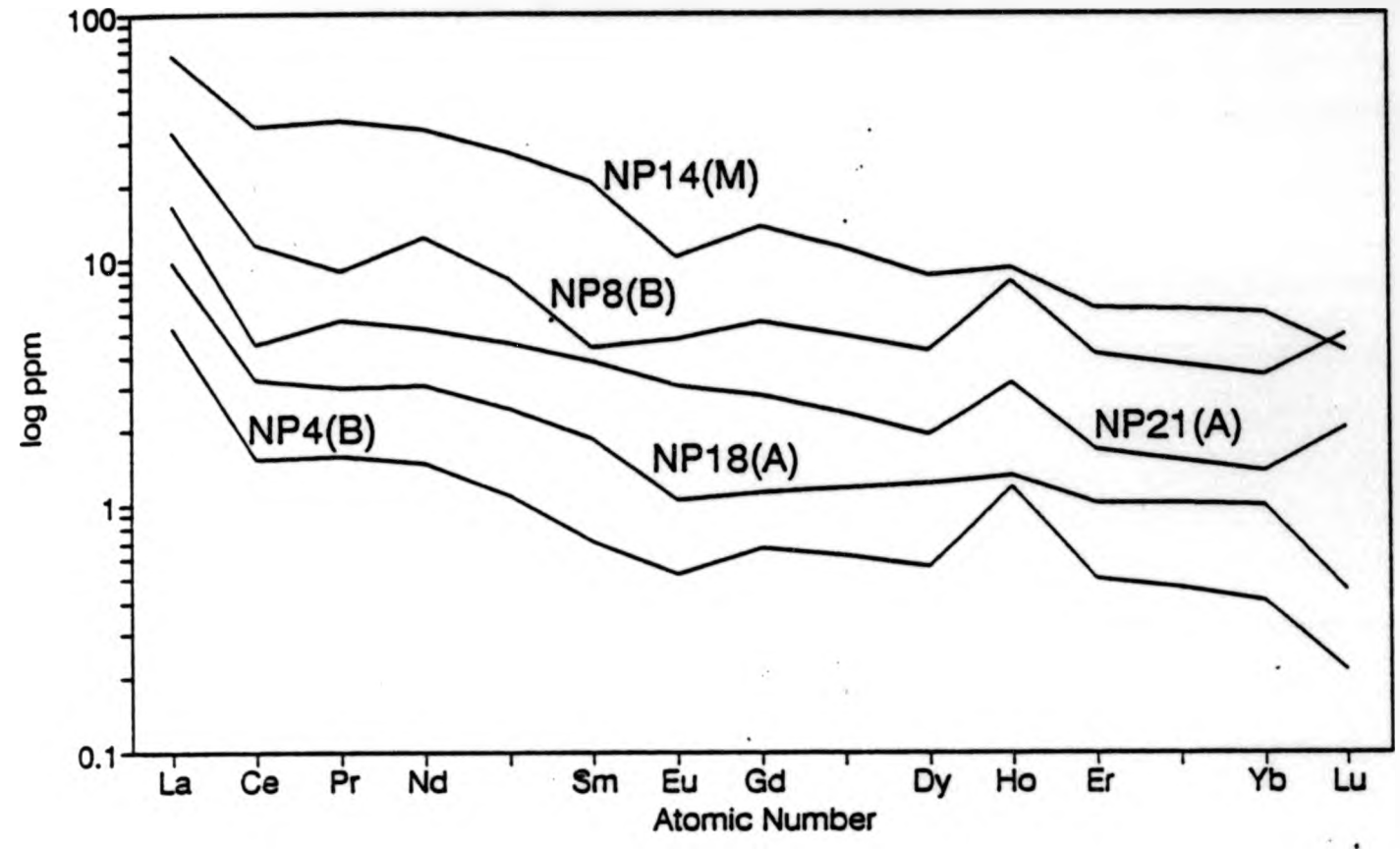
Figure 6.7

CHONDRITE AND SHALE NORMALISED RARE-EARTH ELEMENT PATTERNS ACROSS NEW PIT MARL 2, BEACHY HEAD.

results show that white and marly chalk have similar trends which when normalized to shale are sub-horizontal. Please note that to improve clarity the actual values obtained in both cases have been multiplied by the amounts shown at the bottom of the shale normalized graph prior to plotting.

NP21(A)	100 cm above the marl seam.
NP18(A)	15 cm above the marl seam.
NP14(M)	marl seam.
NP8(B)	20 cm below the marl seam.
NP4(B)	130 cm below the marl seam.

NEW PIT MARL 2, BEACHY HEAD
Chondrite Normalized (Evensen, 1978)



NEW PIT MARL 2, BEACHY HEAD
Shale Normalized (Piper, 1974)

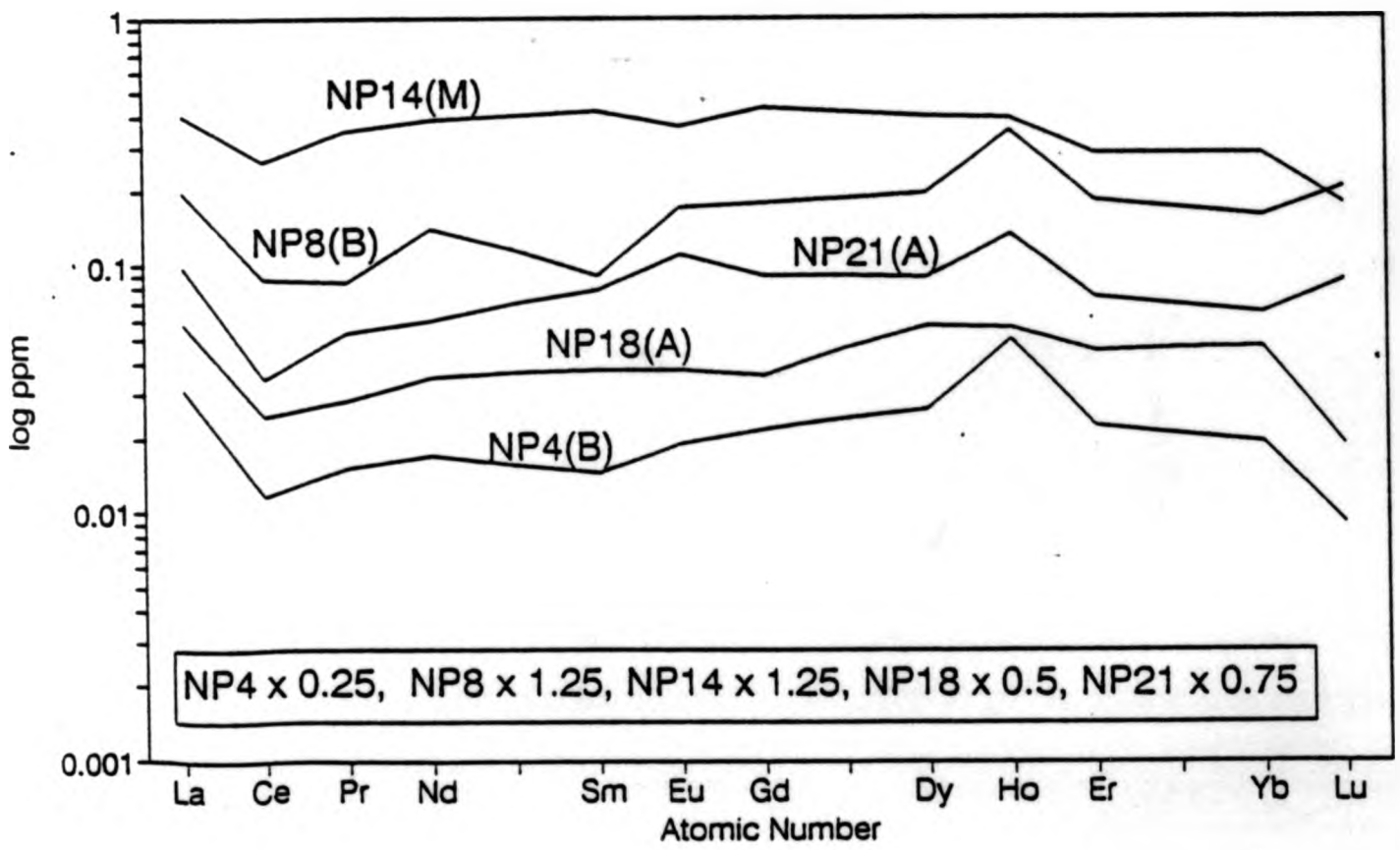
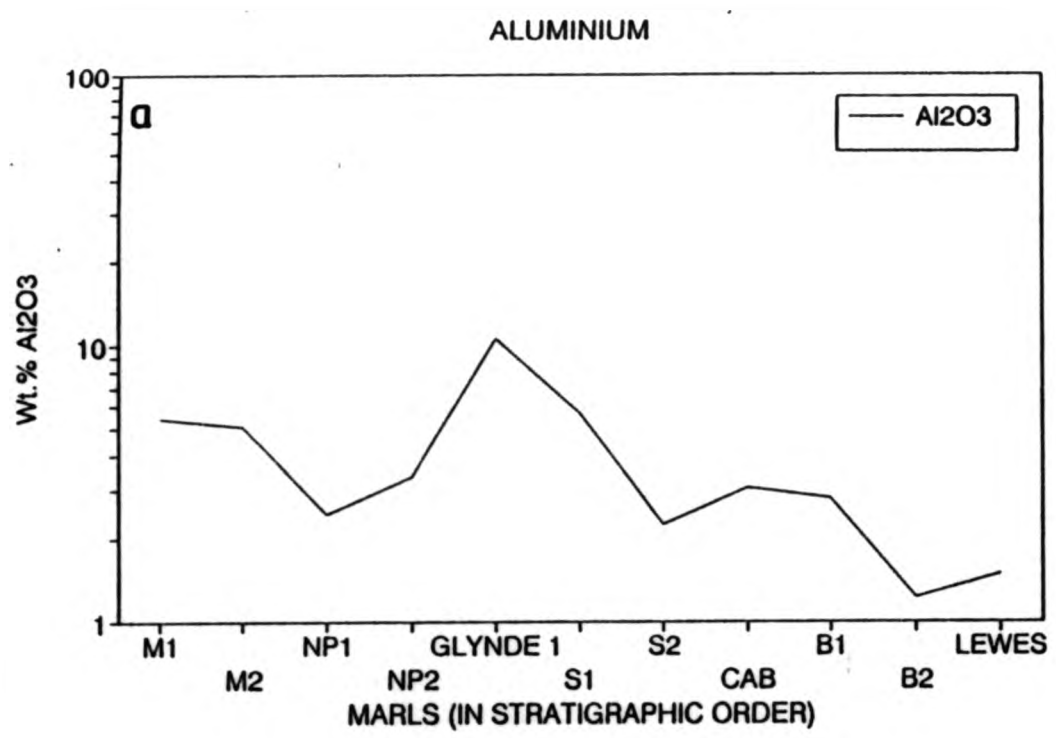


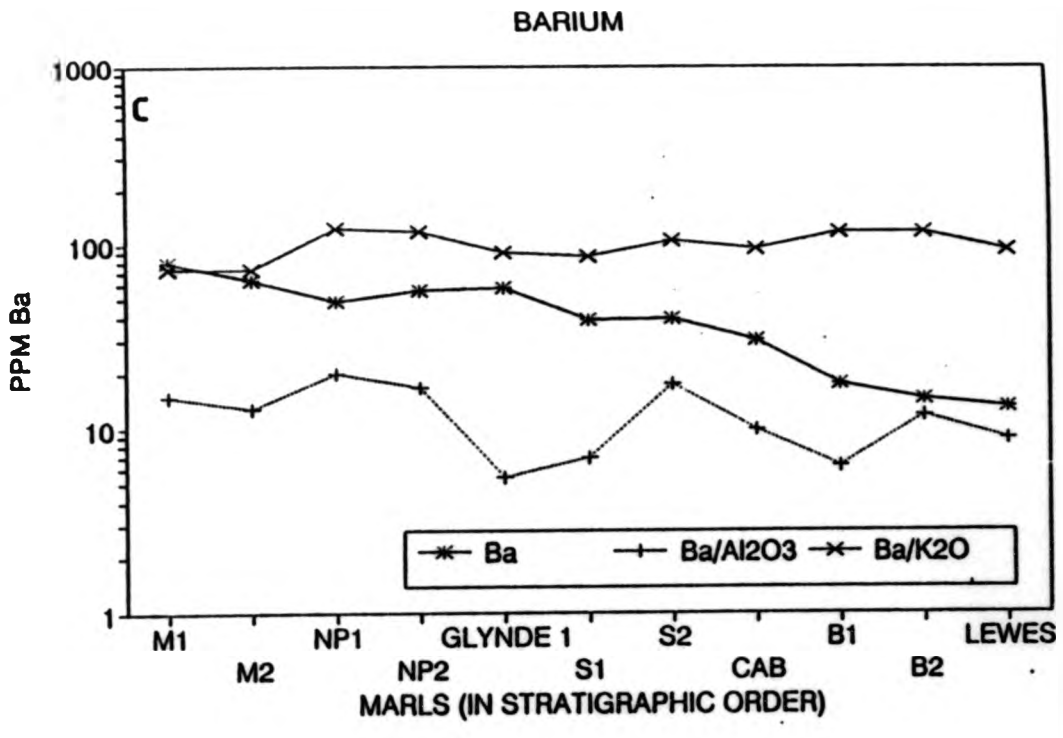
Figure 6.8

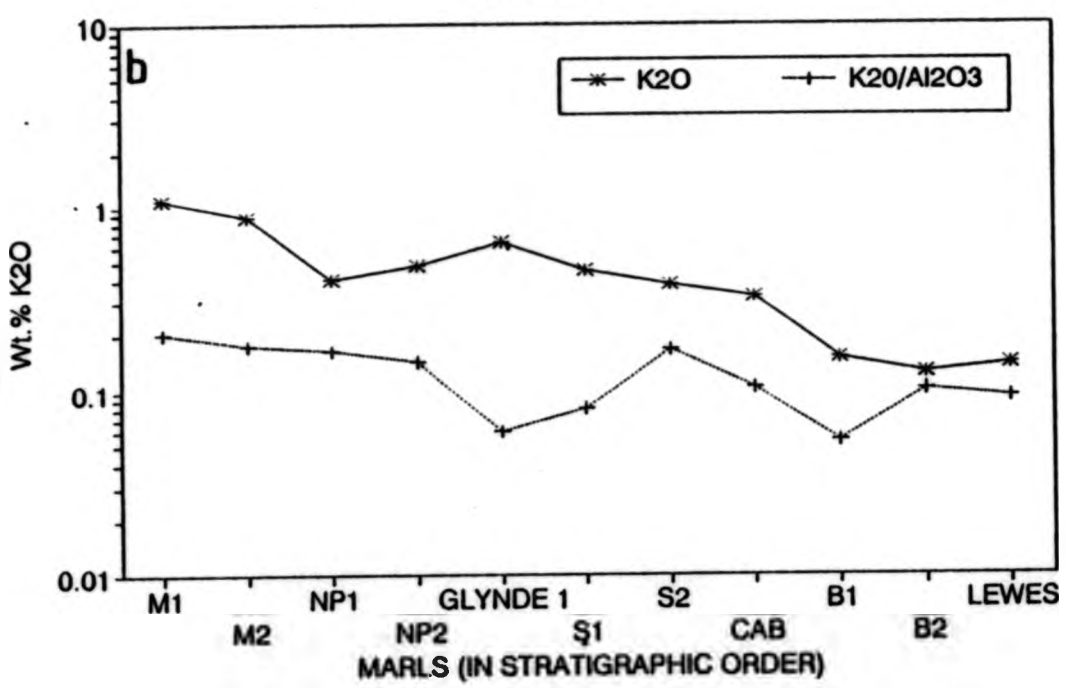
STRATIGRAPHIC TRENDS OF MAJOR AND TRACE ELEMENTS FROM MIDDLE AND UPPER TURONIAN MARLS IN SUSSEX

Also displayed are their aluminium and potassium normalized plots. Elements which show a near-horizontal potassium normalized trend are probably associated with illite. Elements associated with smectite should have more irregular and upward climbing potassium normalized trends. PLEASE NOTE THAT SPACING BETWEEN MARLS IS NOT TO SCALE.

a. Aluminium
b. Potassium
c. Barium
d. Copper
e. Iron
f. Lithium
g. Magnesium
h. Nickel
i. Phosphorous
j. Scandium
k. Silica
l. Sodium
m. Titanium
n. Vanadium
o. Yttrium
p. Zinc
q. Zirconium







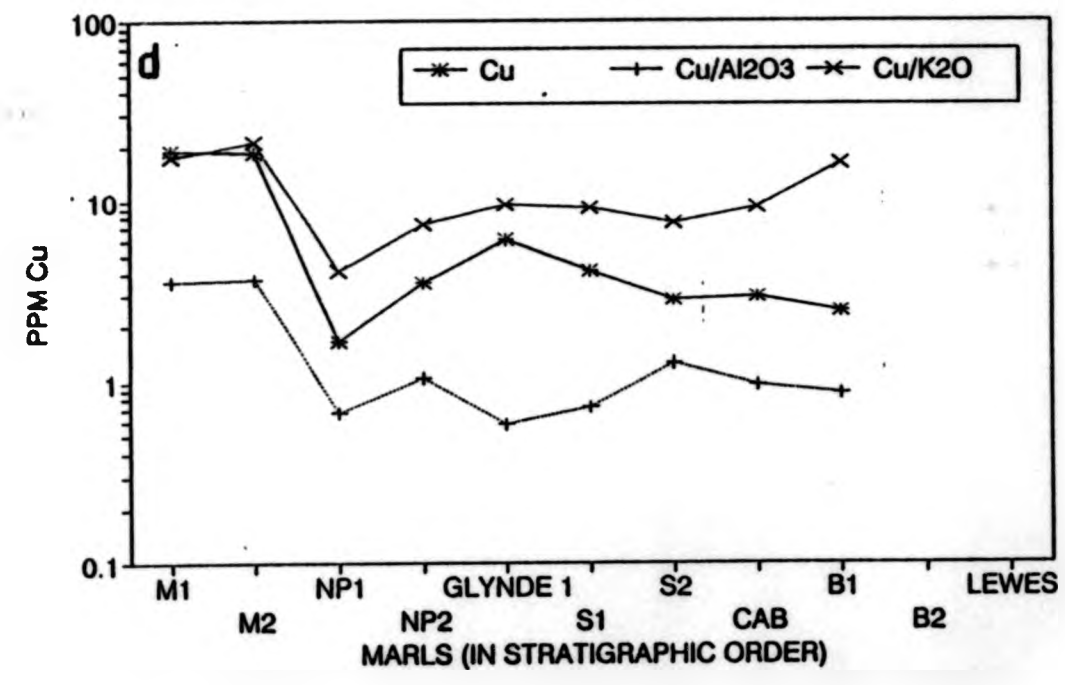
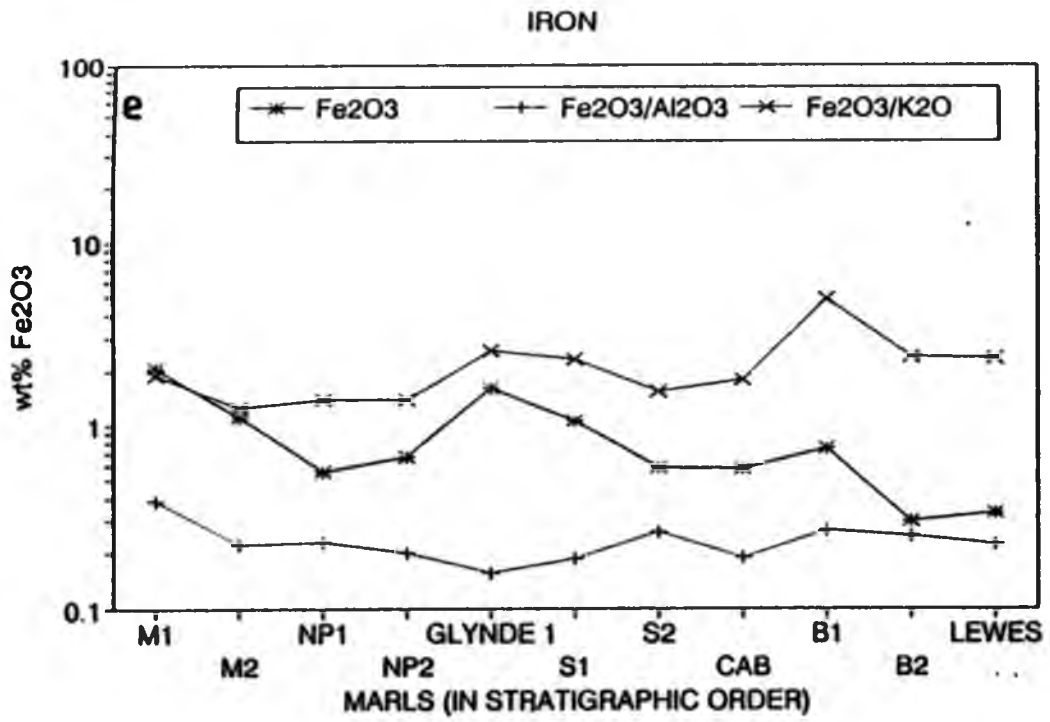
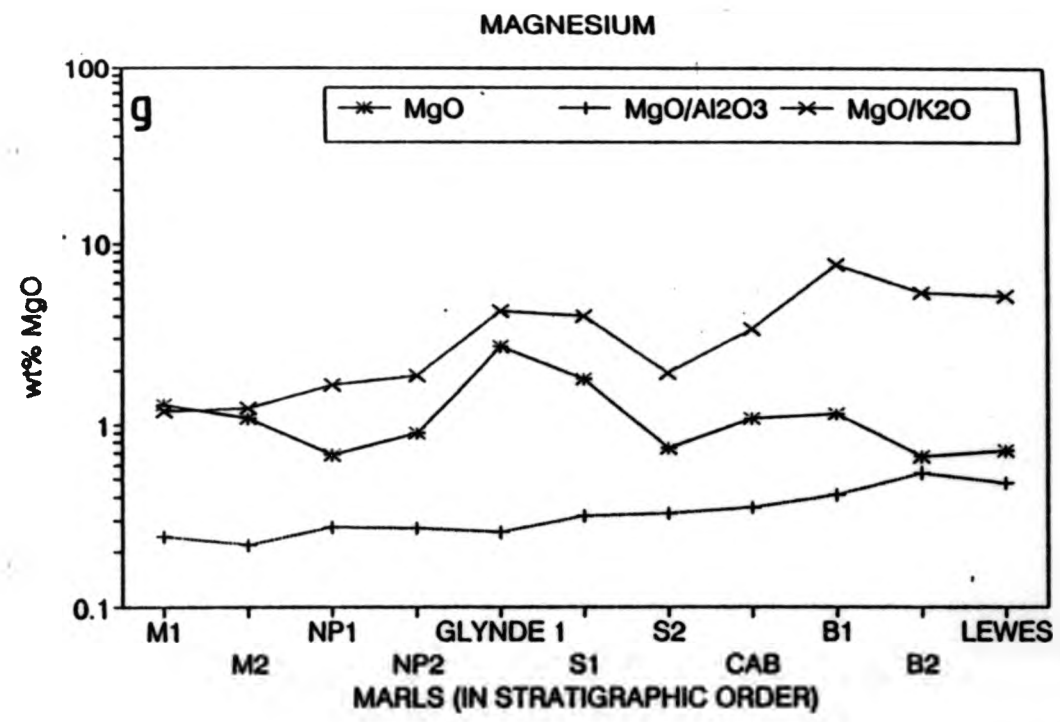
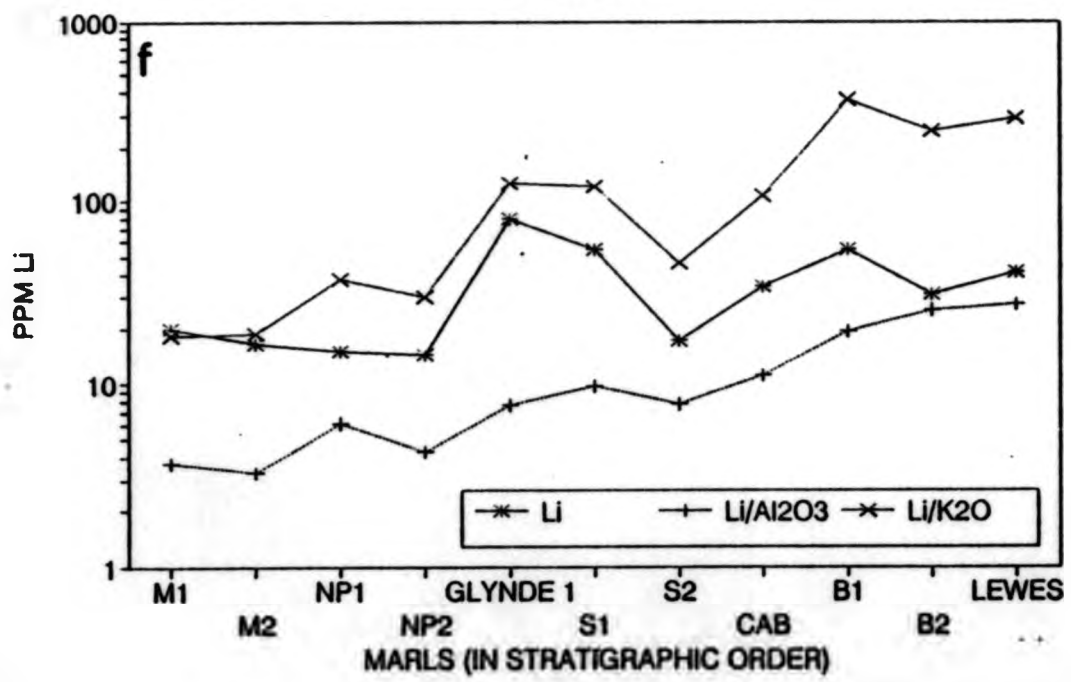


Figure 6.8 cont.







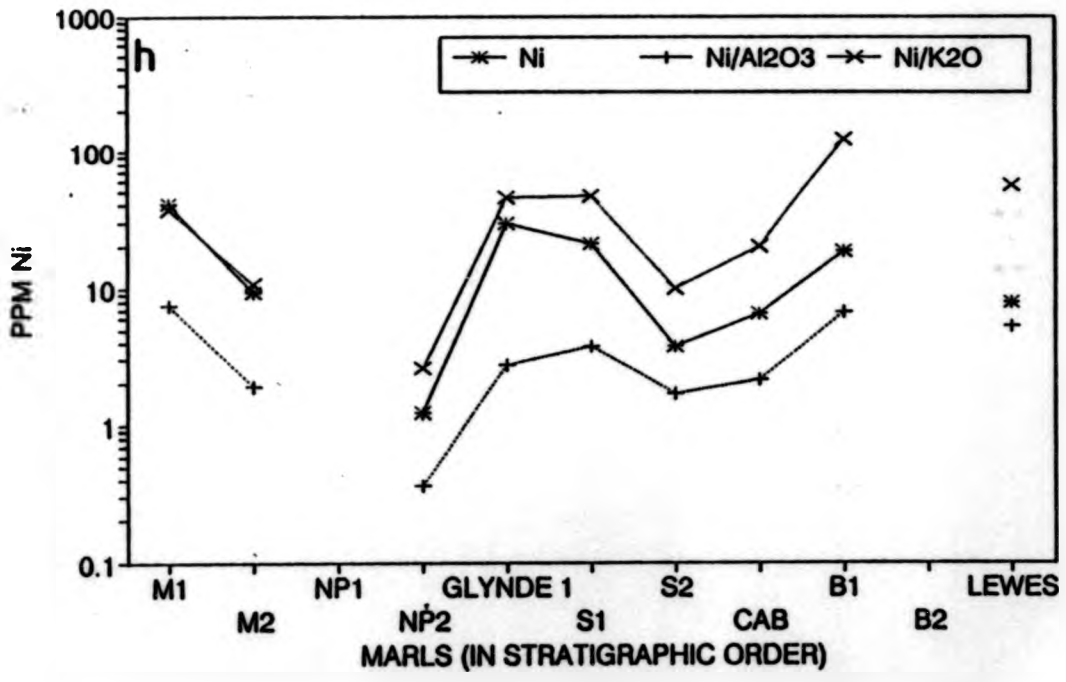
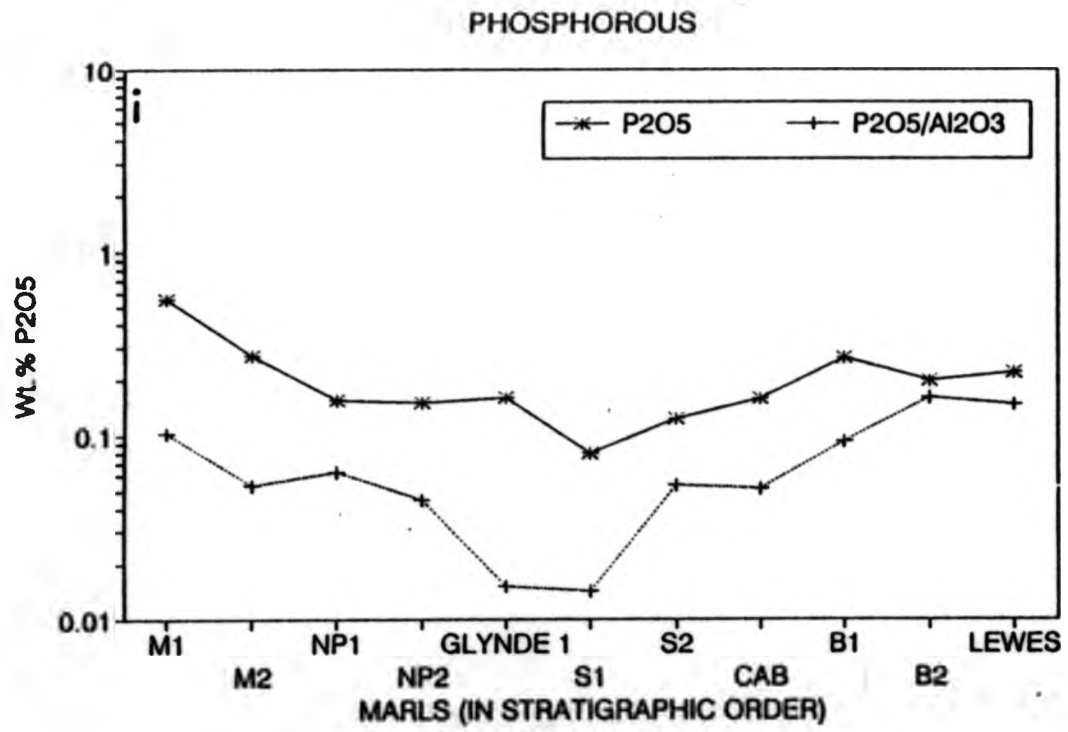
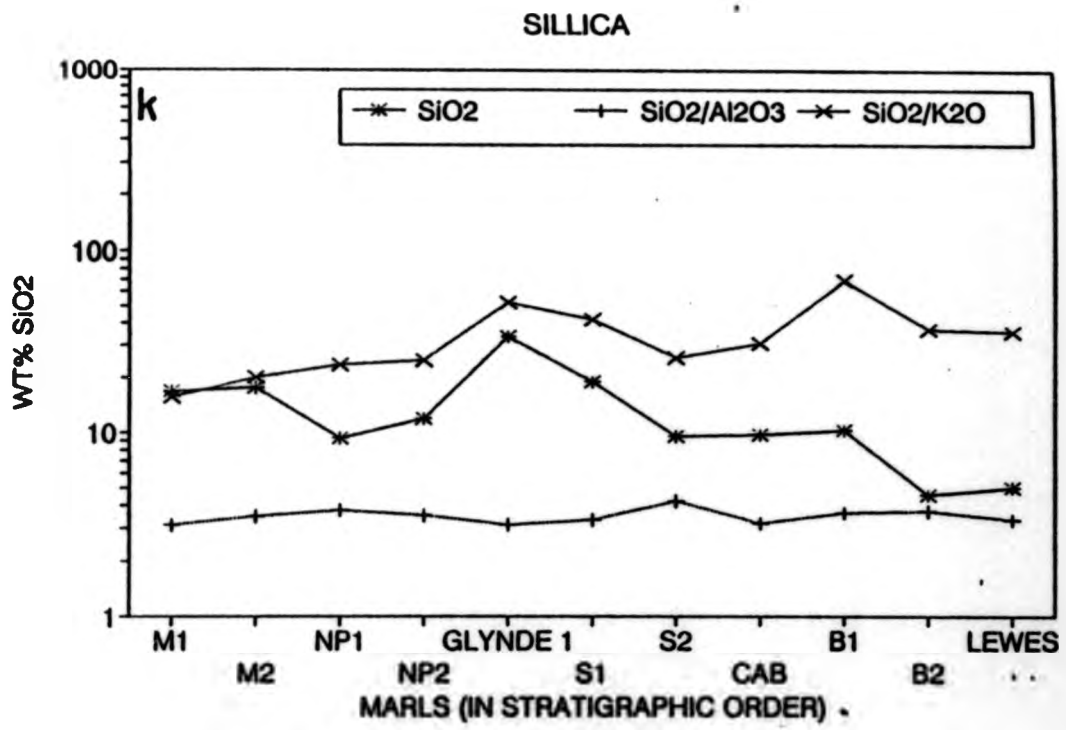
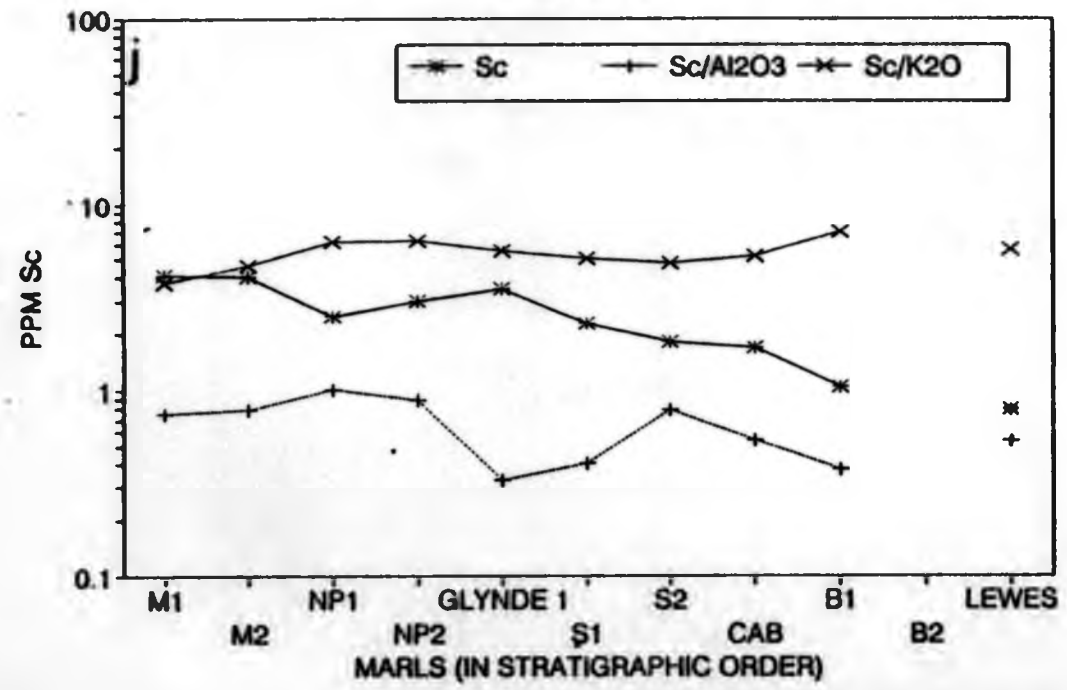


Figure 6.8 cont.







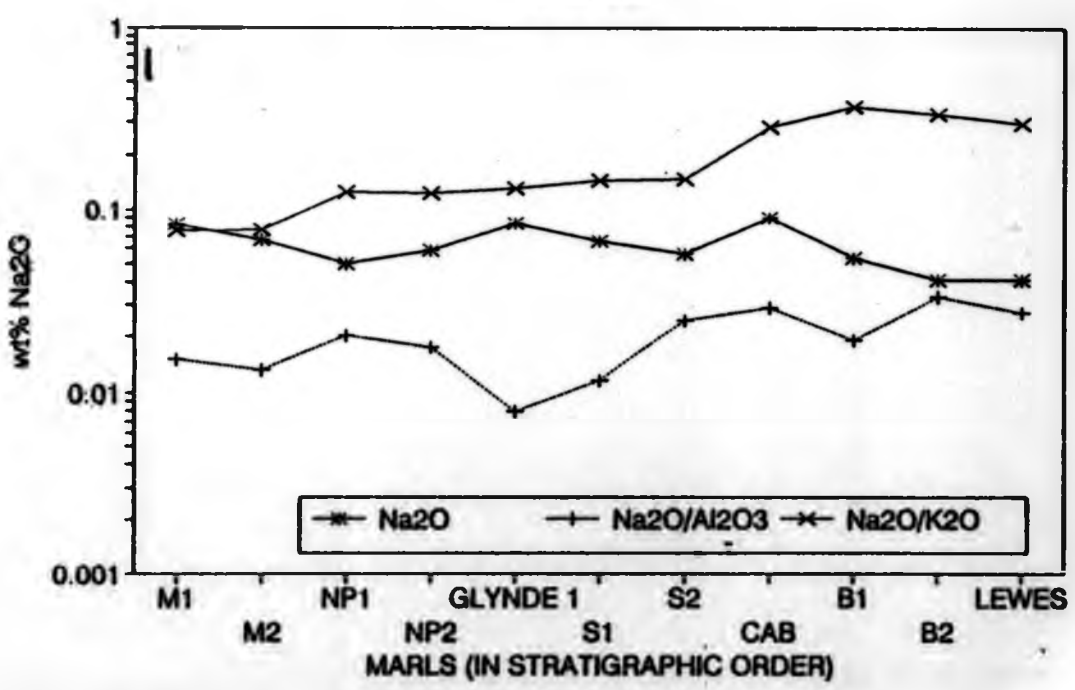
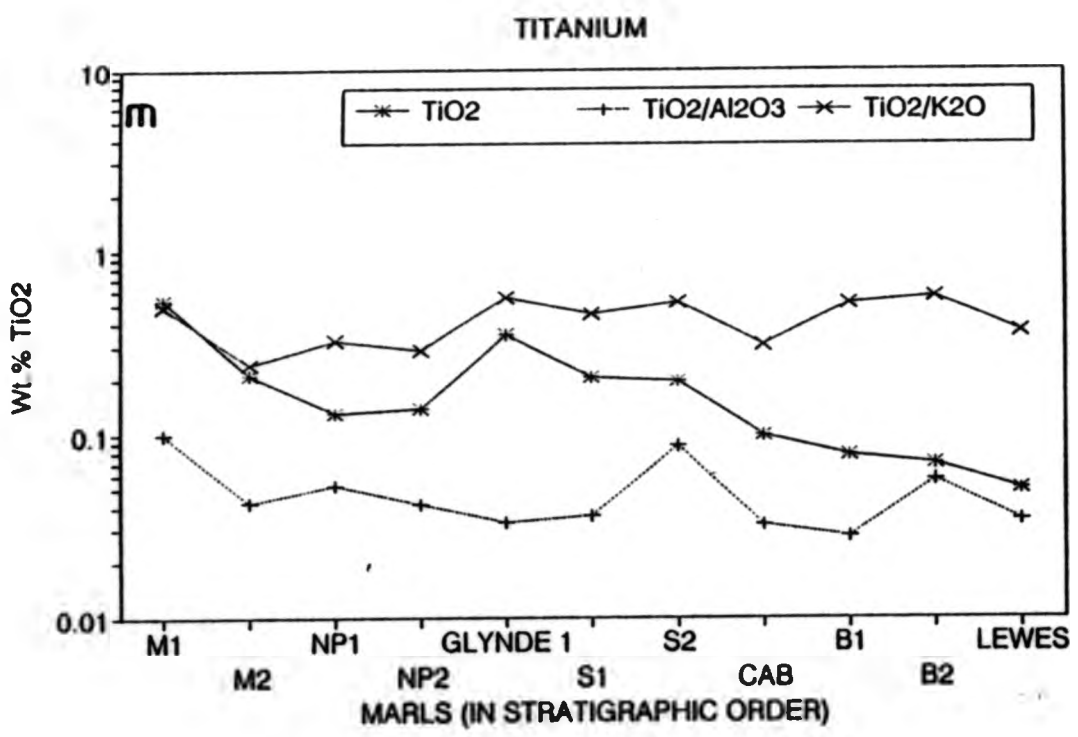
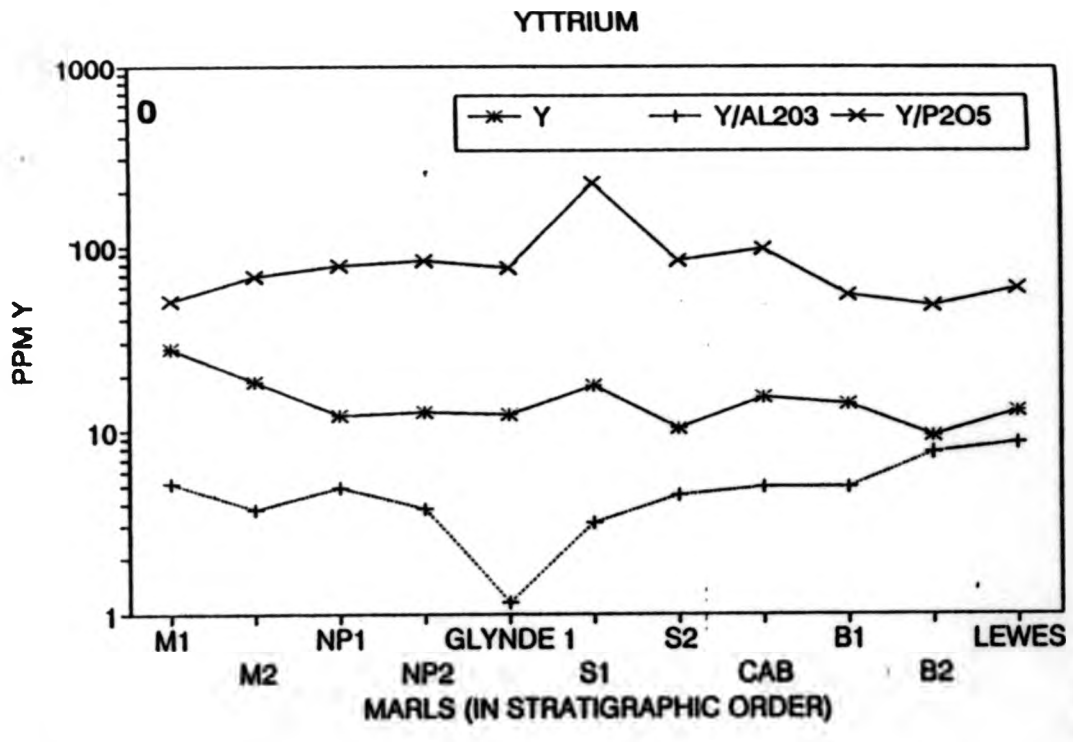
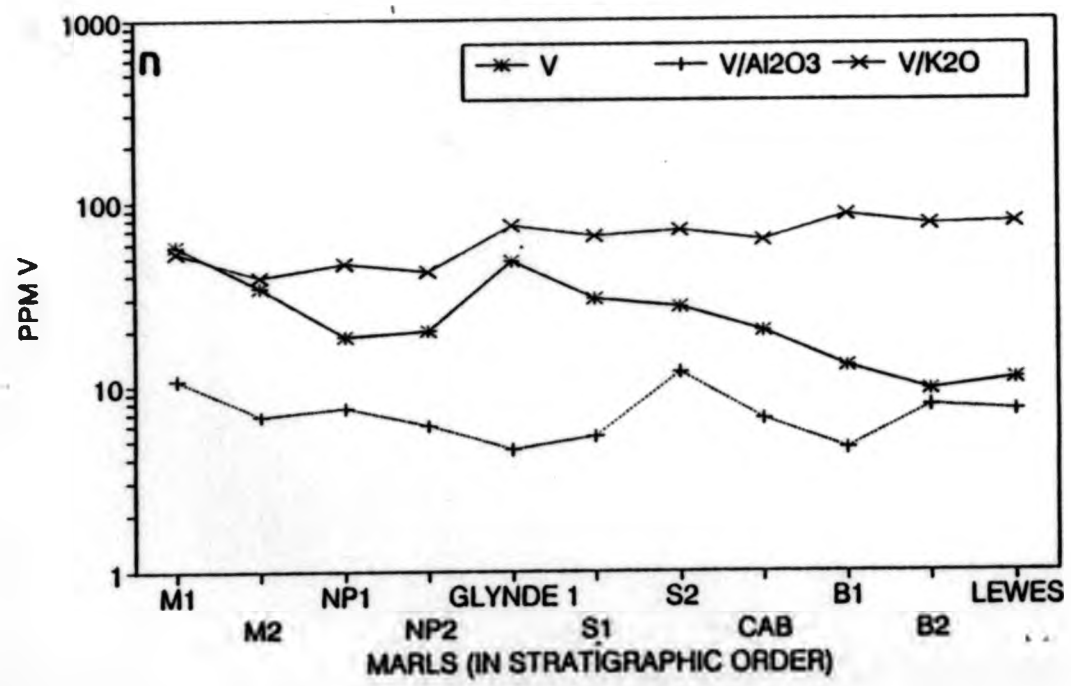


Figure 6.8 cont.







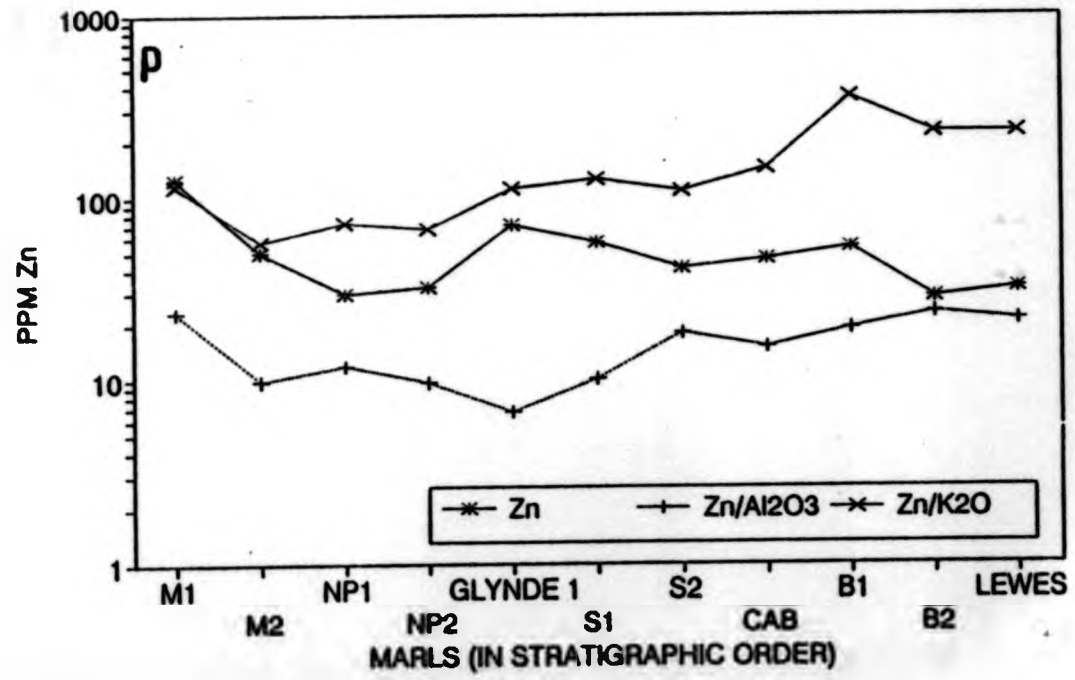


Figure 6.8 cont.

Figure 6.8 cont.

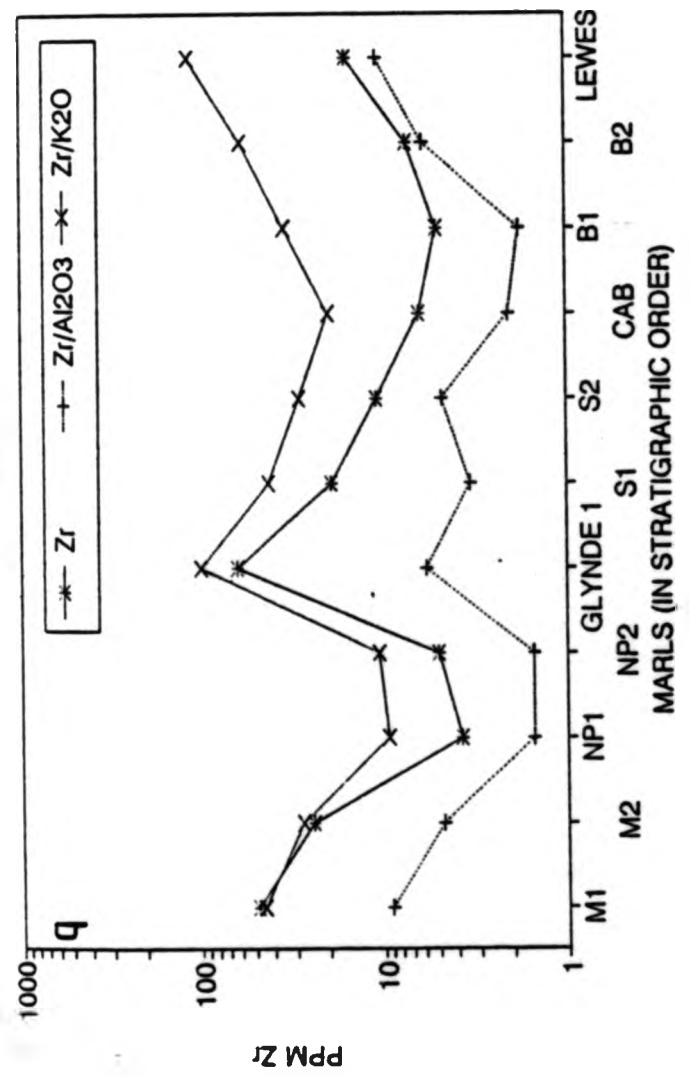


Figure 6.9

CHONDRITE AND SHALE NORMALISED RARE-EARTH ELEMENT PATTERNS OF MIDDLE TURONIAN MARLS FROM SUSSEX

The trends are remarkably consistent, and are near-horizontal when normalized to average shale. Please note that to improve clarity the actual values obtained in both cases have been multiplied by the amounts shown at the bottom of the shale normalized graph prior to plotting.

C Caburn Marl

S2 Southerham Marl 2

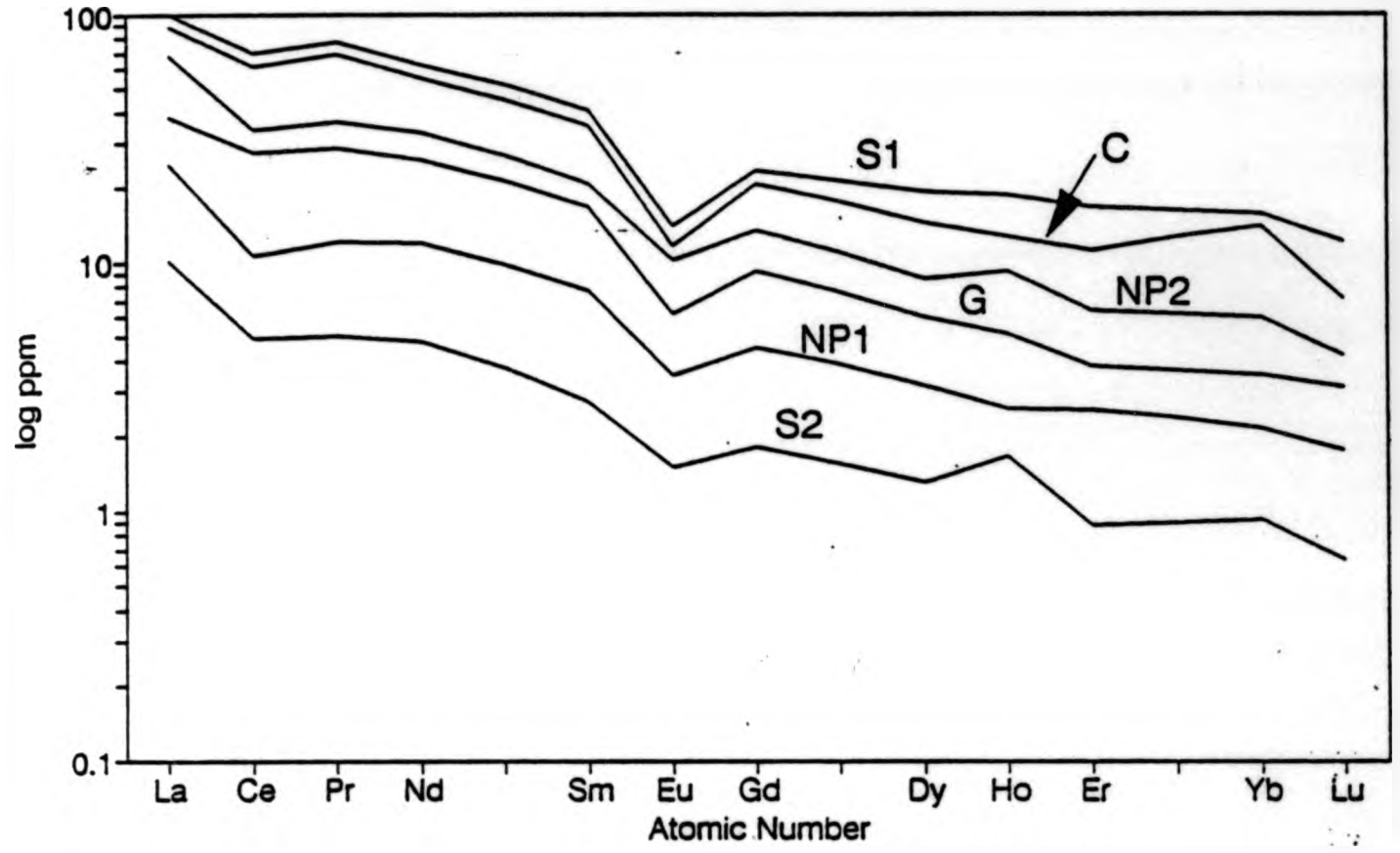
S1 Southerham Marl 1

G Glynde Marl 1 [Caburn]

NP2 New Pit Marl 2

NP1 New Pit Marl 1

MIDDLE TURONIAN MARLS (SUSSEX)
Chondrite Normalized (Evensen, 1978)



MIDDLE TURONIAN MARLS (SUSSEX)
Shale Normalized (Piper, 1974)

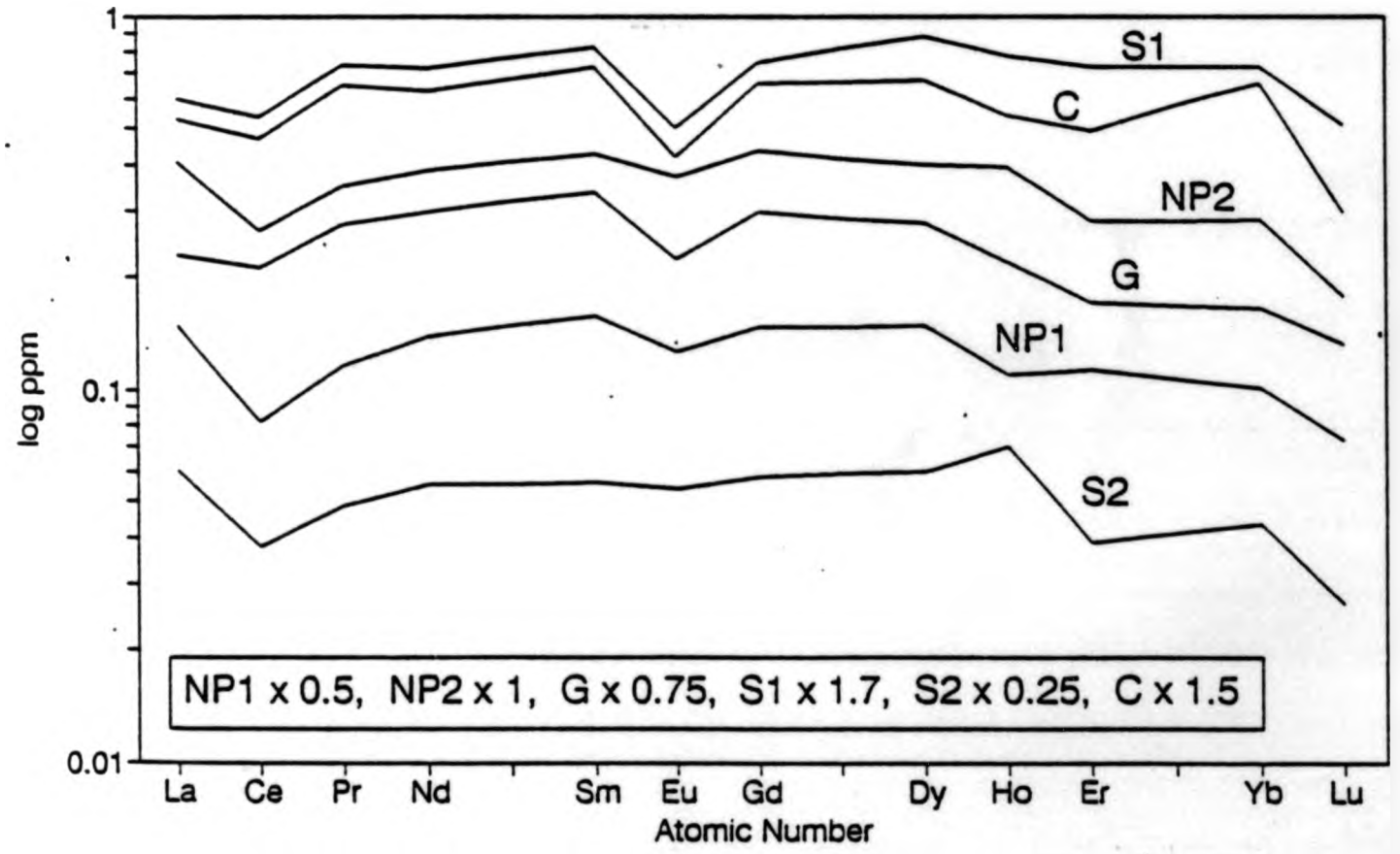


Figure 6.10

CHONDRITE AND SHALE NORMALISED RARE-EARTH ELEMENT PATTERNS OF UPPER TURONIAN MARLS FROM SUSSEX

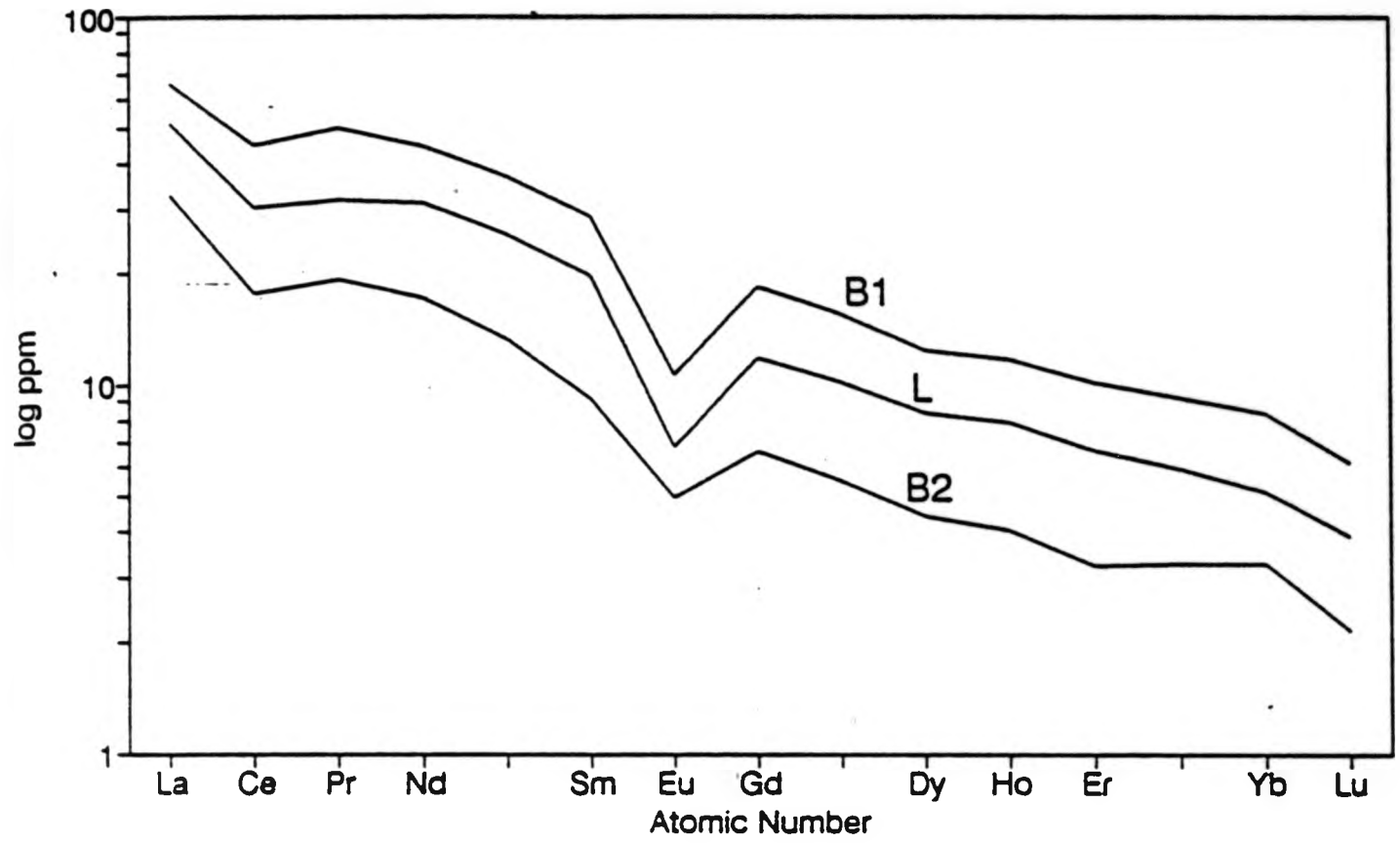
As with the samples from the Middle Turonian; the trends are remarkably consistent, and are near-horizontal when normalized to shale. Please note that to improve clarity the actual values obtained in both cases have been multiplied by the amounts shown at the bottom of the shale normalized graph prior to plotting.

L Lewes Marl

B2 Bridgewick Marl 2

B1 Bridgewick marl 1

UPPER TURONIAN MARLS (SUSSEX)
Chondrite Normalized (Evensen, 1978)



UPPER TURONIAN MARLS (SUSSEX)
Shale Normalized (Piper, 1974)

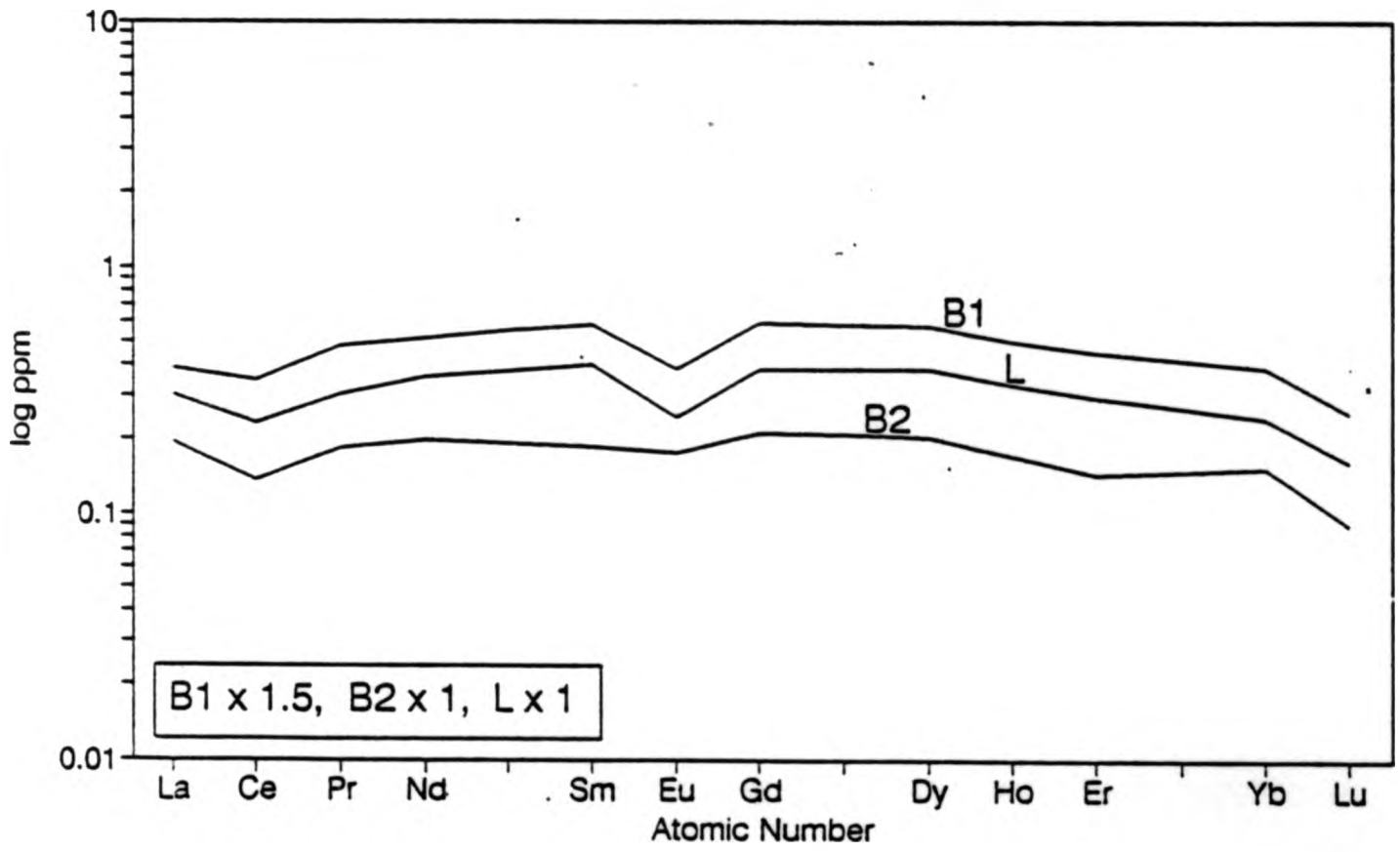
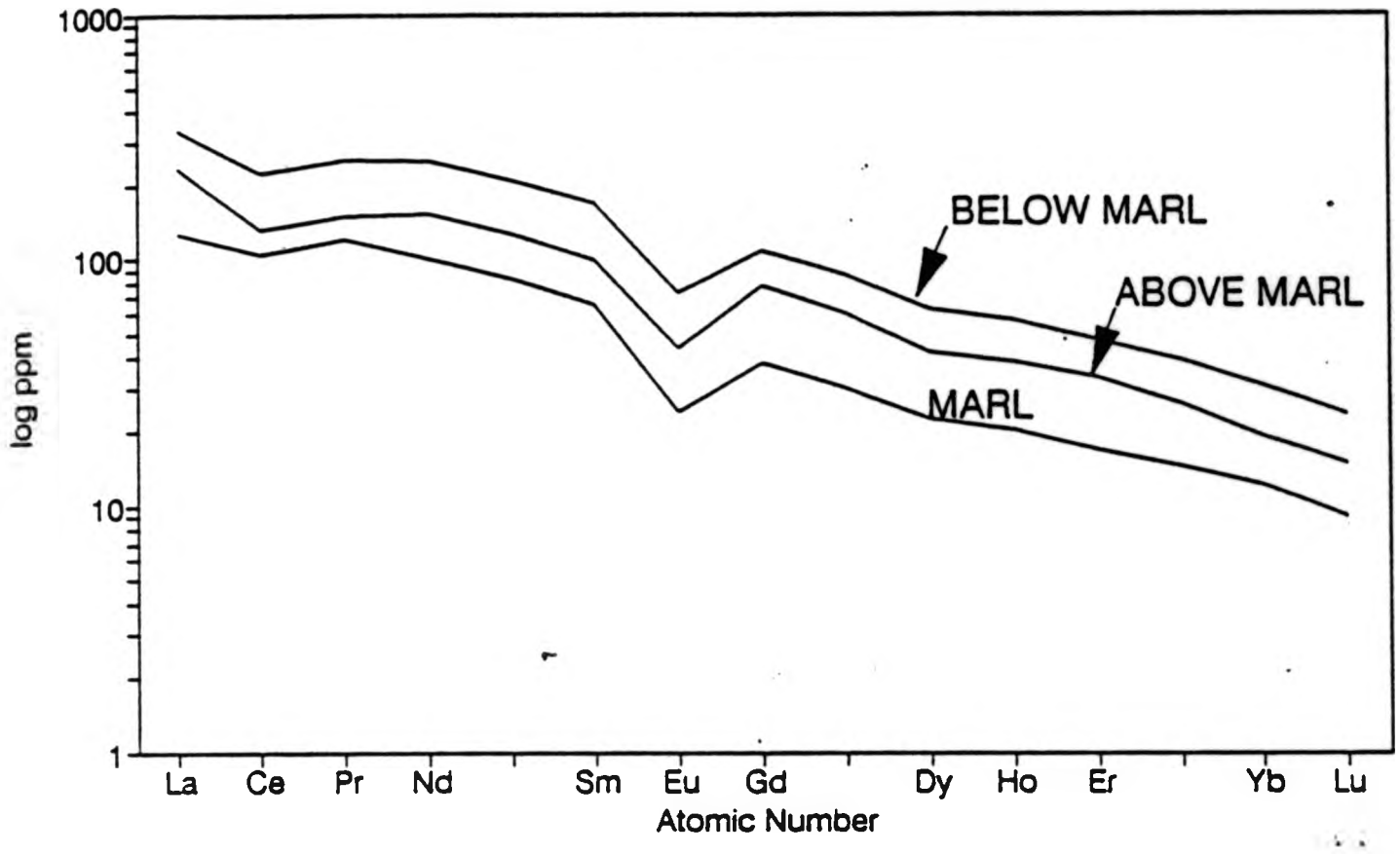


Figure 6.11

CHONDRITE AND SHALE NORMALISED RARE-EARTH ELEMENT PATTERNS OF THREE INSOLUBLE RESIDUES FROM SOUTHERHAM MARL 1

Chondrite and shale normalized rare earth element patterns of three insoluble residues from below, within, and above Southerham Marl 1 at Great Chesterford displaying parallel trends.

I.R. SOUTHERHAM 1, GREAT CHESTERFORD
Chondrite Normalized (Evensen, 1978)



I.R. SOUTHERHAM 1 GREAT CHESTERFORD.
Shale Normalized (Piper, 1974)

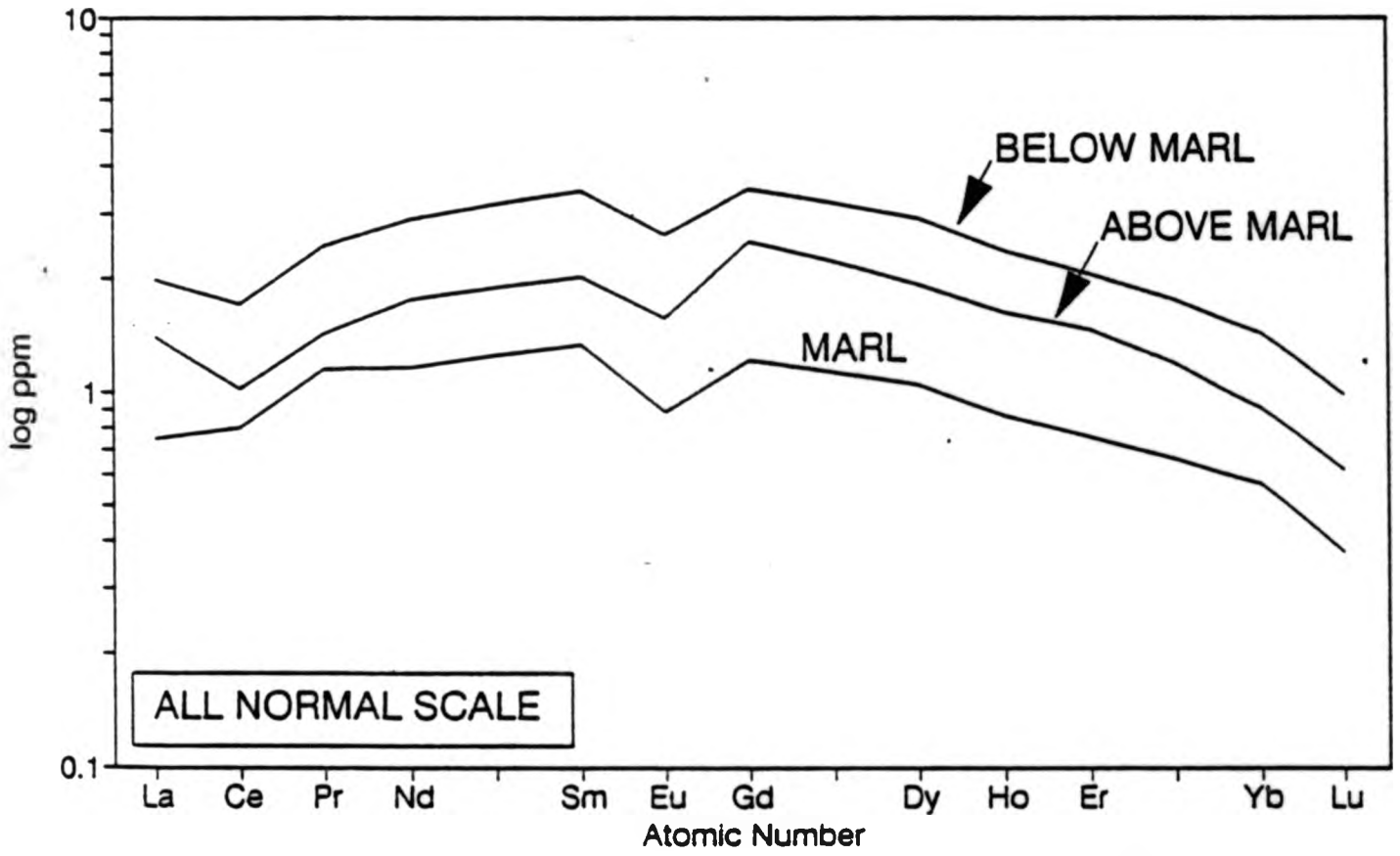


Figure 6.12

$\delta^{18}O$ AND $\delta^{13}C$ RESULTS ACROSS NEW PIT MARL 2. BEACHY HEAD.

The $\delta^{18}O$ trend displays a marked enrichment in ^{18}O within the marl and a slight depletion directly above. $\delta^{13}C$ decreases gradually up-section and is not affected by the marl seam.

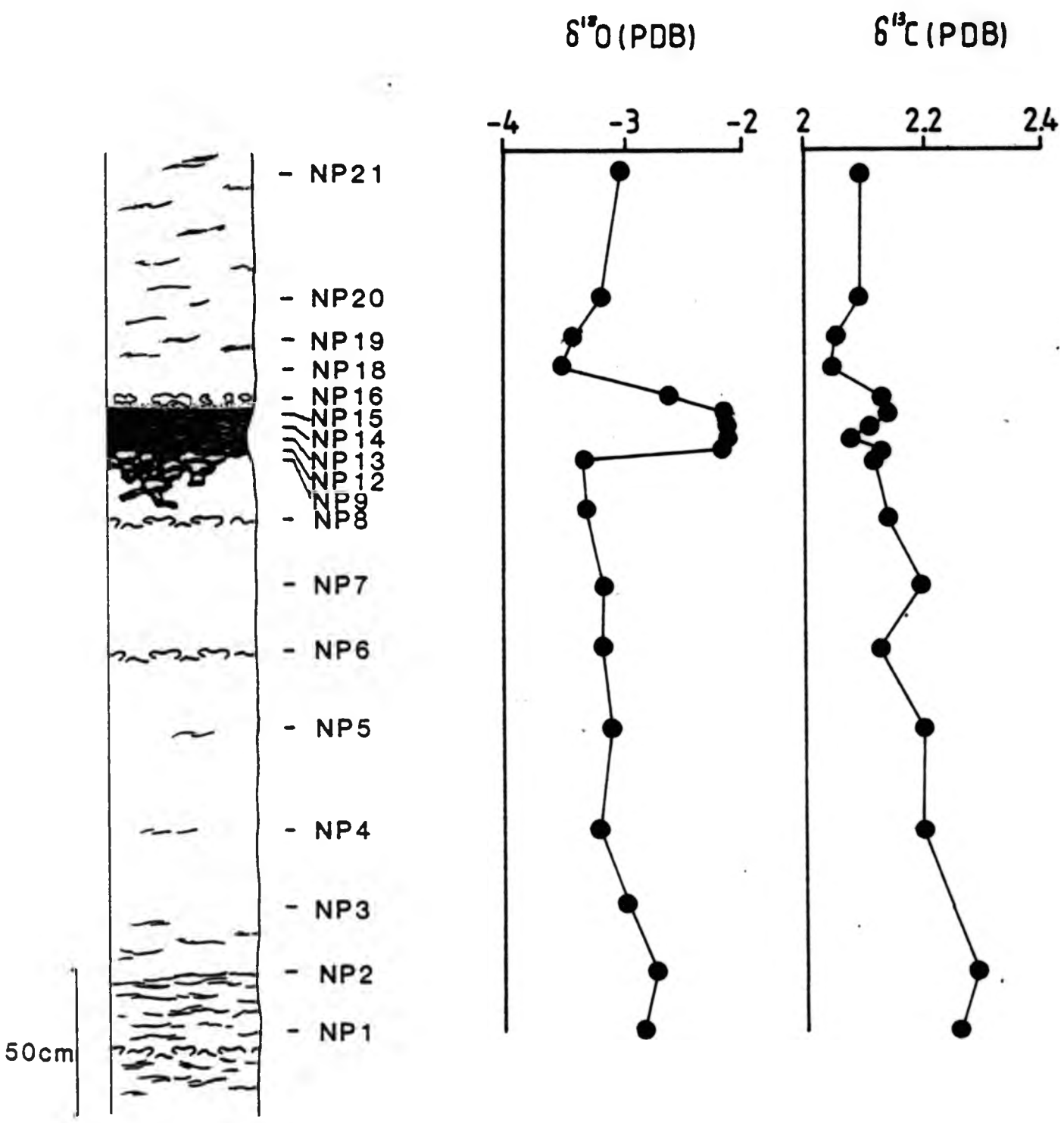

δ18O (PDB)
δ13C (PDB)
-4
-3
-2
2
2.2
2.4
NP21
NP20
NP19
NP18
NP16
NP15
NP14
NP13
NP12
NP9
NP8
NP7
NP6
NP5
NP4
NP3
NP2
NP1
50cm

Figure 6.13

DIFFERENCES IN $\delta^{18}O$ AND $\delta^{13}C$ RESULTS FROM PAIRED WHITE AND MARLY CHALK SAMPLES

Results consistently show enrichment of ^{18}O within the marl. There is no consistent difference in $\delta^{13}C$ between white and marly chalks, the scattering of the paired samples is due to long-term, basin-wide variations.

▲ = marl

● = white chalk

1. New Pit Marl 1, Beachy Head.
2. New Pit Marl 1, Dover.
3. New Pit Marl 2, Dover.
4. New Pit Marl 2, Beachy Head.
5. Glynde Marl 2 [Dover].
6. Glynde Marl 1, Puys.
7. Southerham Marl 1, Eletot.
8. Caburn Marl, Eletot.
9. White chalk below Caburn Marl, Eletot.
10. White chalk below Southerham Marl 1, Eletot.
11. White chalk below Glynde Marl 1, Puys.
12. White chalk above Glynde Marl 2 [Dover].
13. White chalk between New Pit Marls 1 and 2, Beachy Head.
14. White chalk between New Pit Marls 1 and 2, Dover.

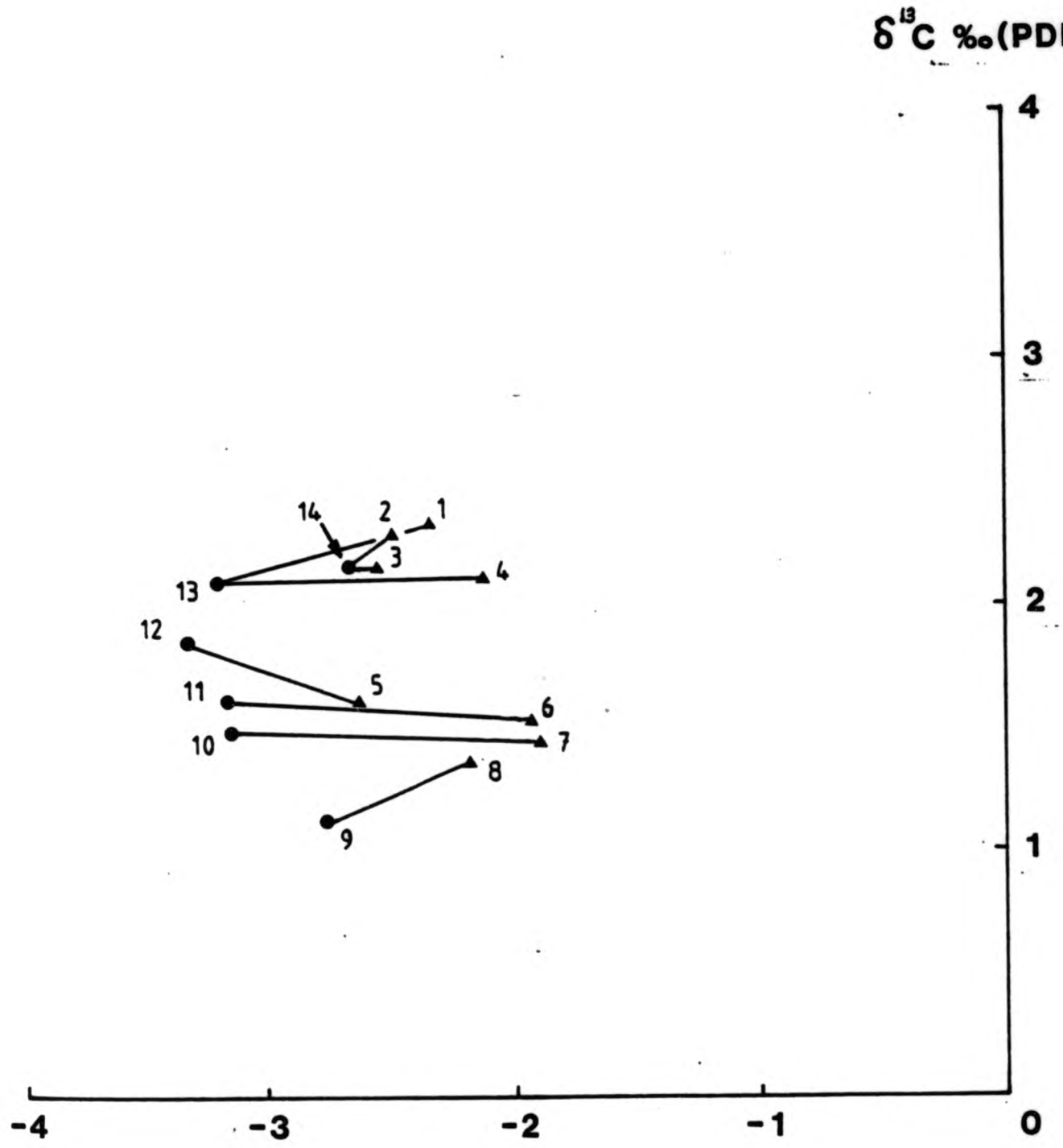

δ13C ‰(PDB)
4
3
2
1
14
2
1
3
13
4
12
5
11
6
10
7
8
9
-4
-3
-2
-1
0
δ18O ‰(PDB)

Figure 6.14

TOTAL ORGANIC CARBON AND $\delta^{13}C$ RESULTS ACROSS NEW PIT MARL 2, BEACHY HEAD.

There is no apparent increase in TOC associated with the marly chalk, although there is a small peak above.

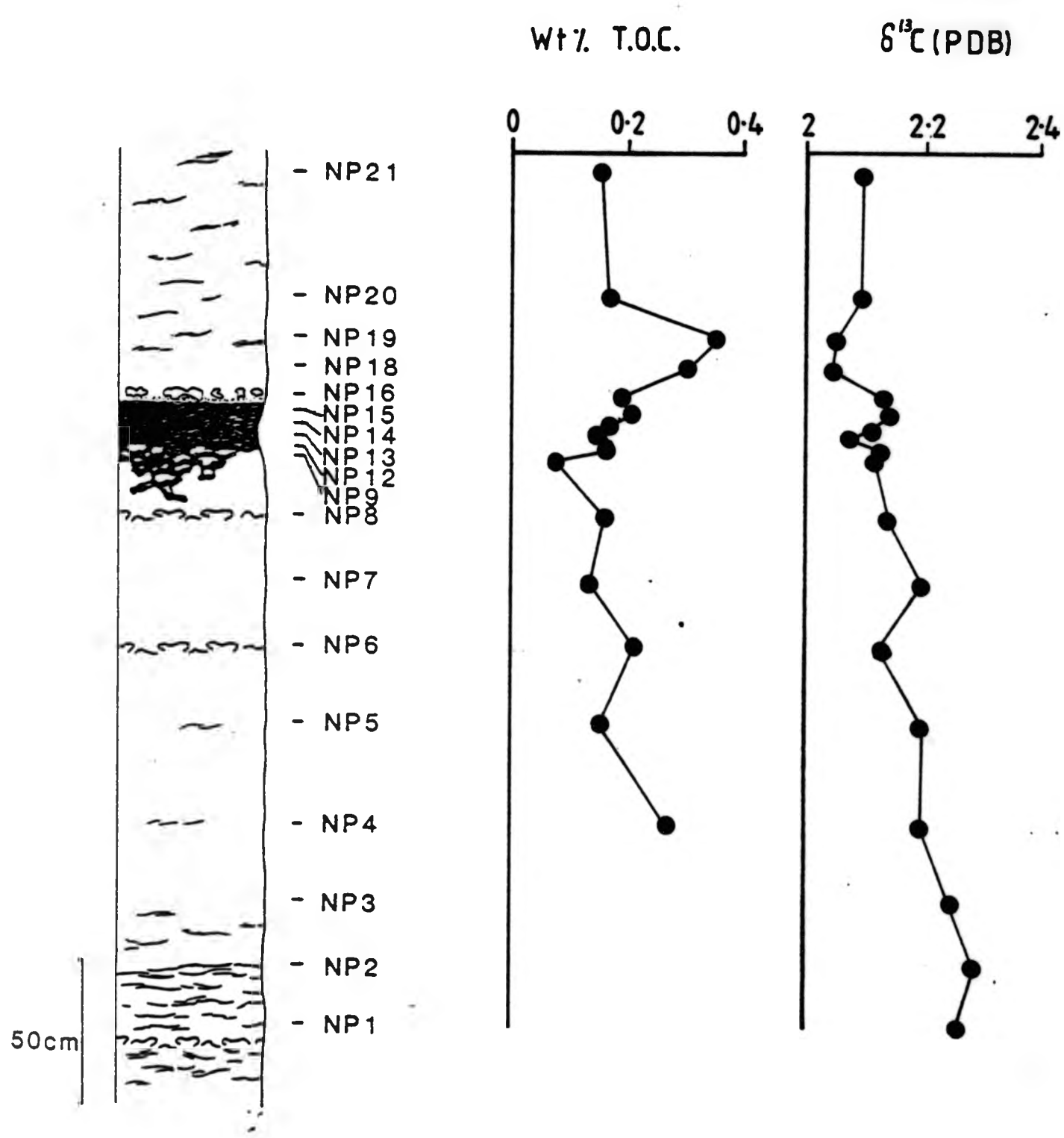

Wt% T.O.C.
δ13C (PDB)
0
0·2
0·4
2
2·2
2·4
NP21
NP20
NP19
NP18
NP16
NP15
NP14
NP13
NP12
NP9
NP8
NP7
NP6
NP5
NP4
NP3
NP2
NP1
50cm

Figure 7.1

A COMPARISON OF MAJOR AND TRACE ELEMENT VARIATIONS OF MIDDLE AND UPPER TURONIAN MARLS FROM KENT, FRANCE AND SUSSEX.

a) Plot of aluminium values from Middle and Upper Turonian marls from Kent, France and Sussex.

b) Plot of potassium values from Middle and Upper Turonian marls from Kent, France and Sussex.

c) - m) and o) - p): plot of aluminium normalized results from Kent, France and Sussex.

c) Potassium

d) Barium

e) Iron

f) Lithium

g) Nickel

h) Magnesium

i) Scandium

j) Silica

k) Titanium

l) Vanadium

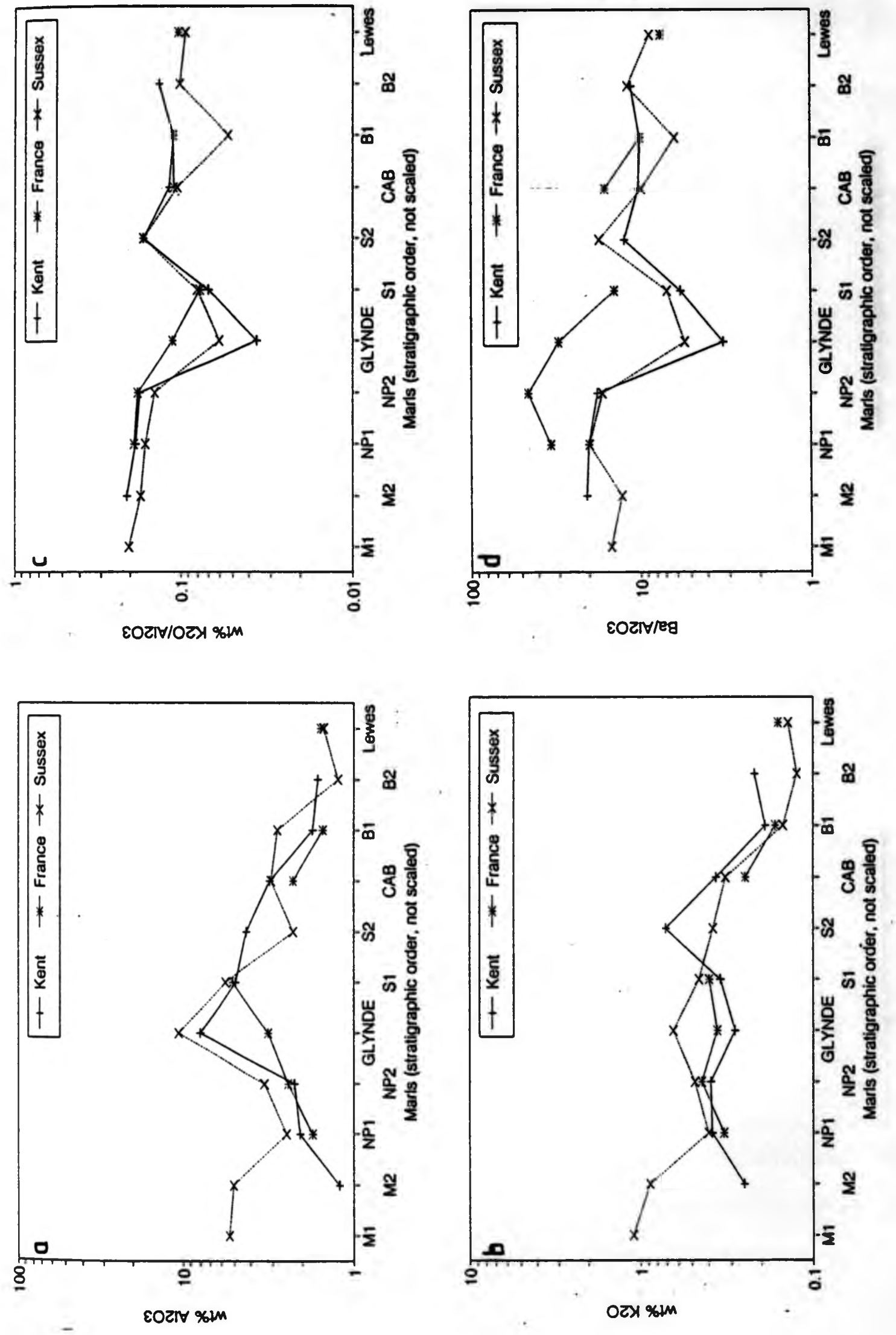
m) Yttrium

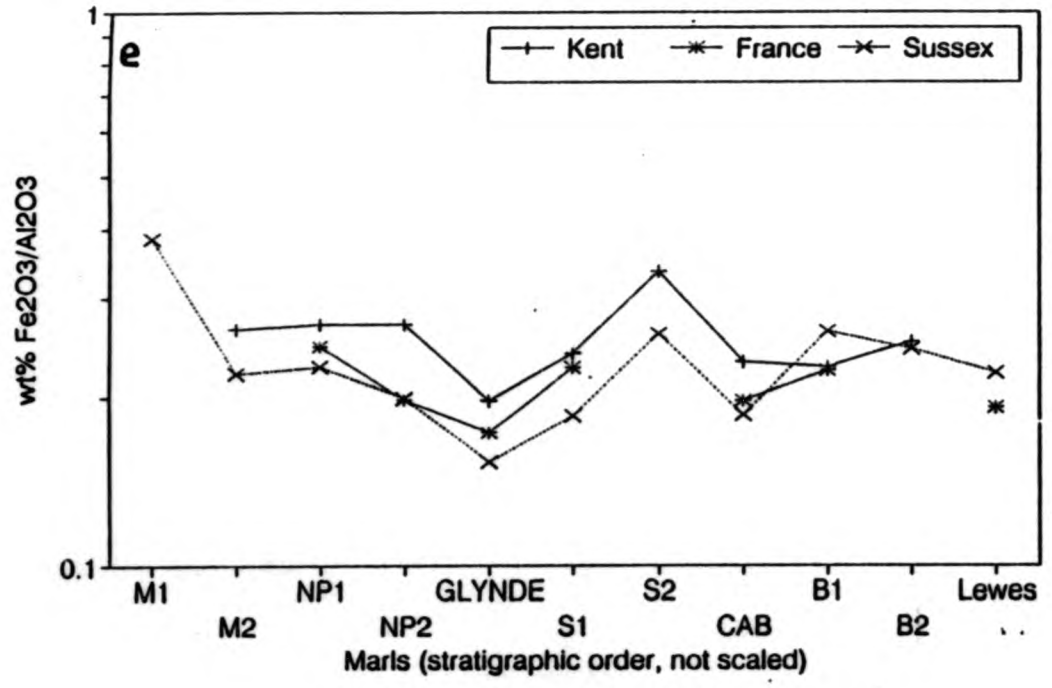
n) Plot of phosphorous normalized yttrium

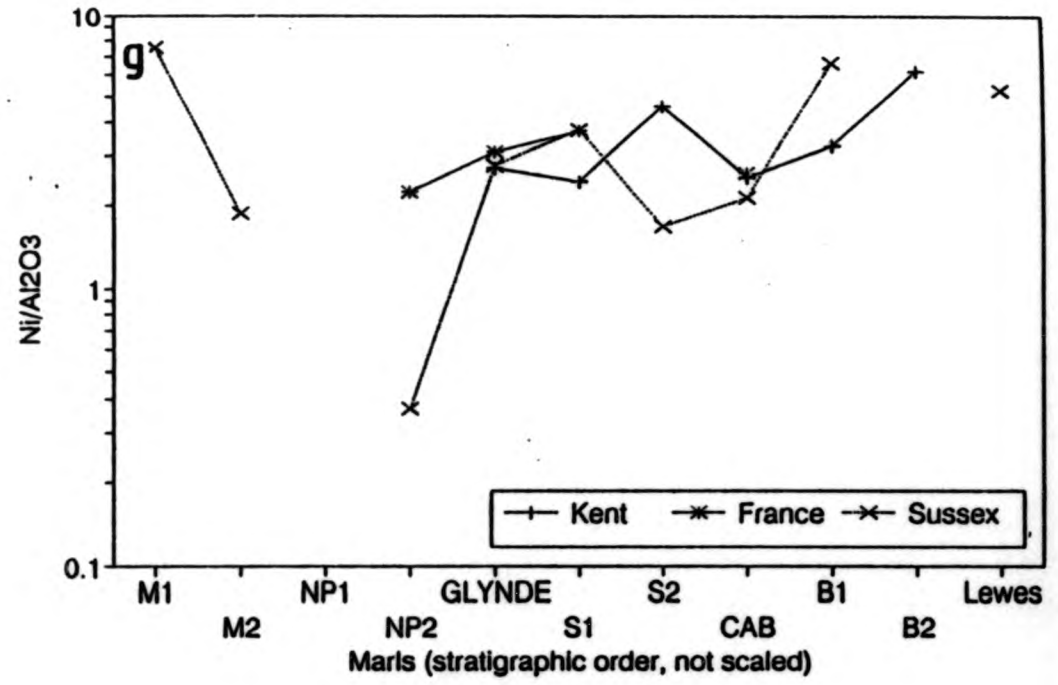
o) Zinc

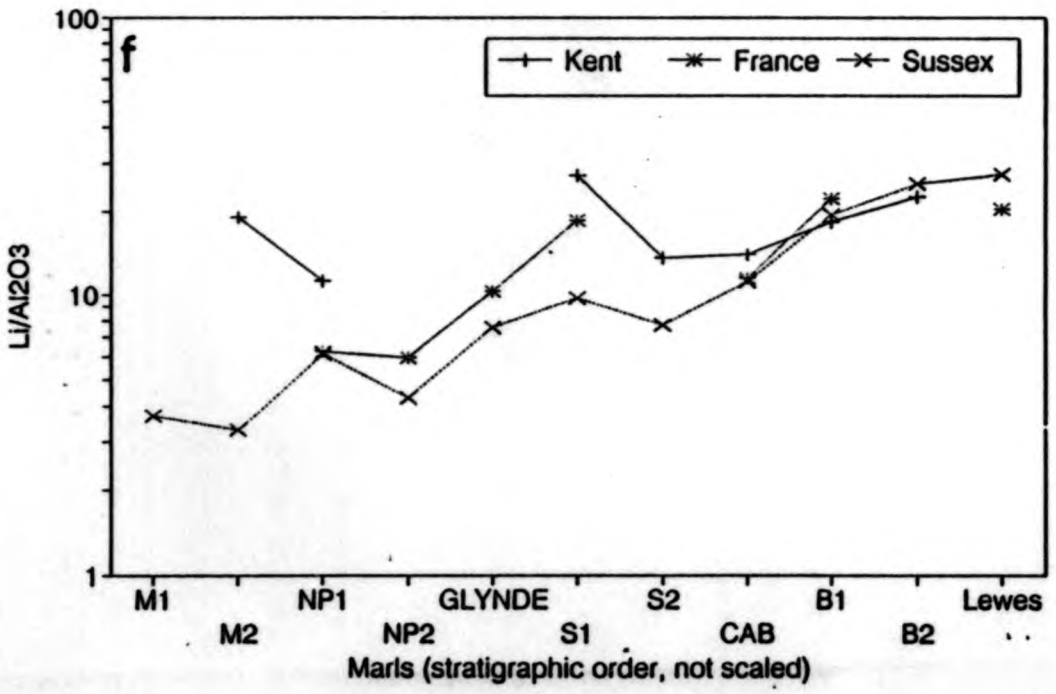
p) Zirconium

Figure 7.1 cont.









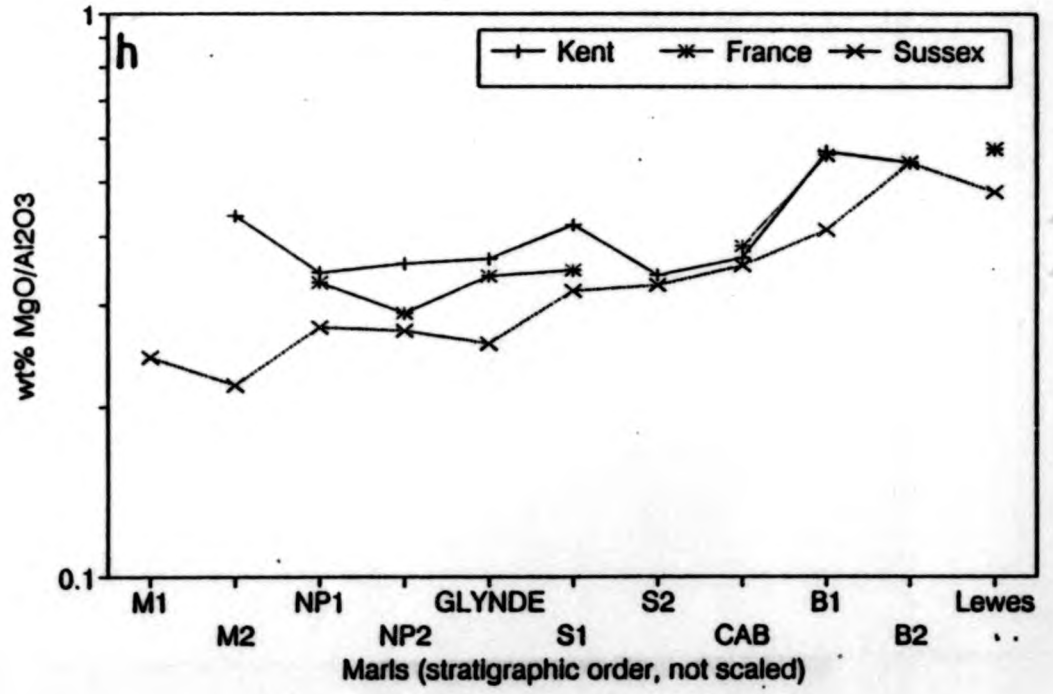


Figure 7.1 cont.

Figure 7.1 cont.

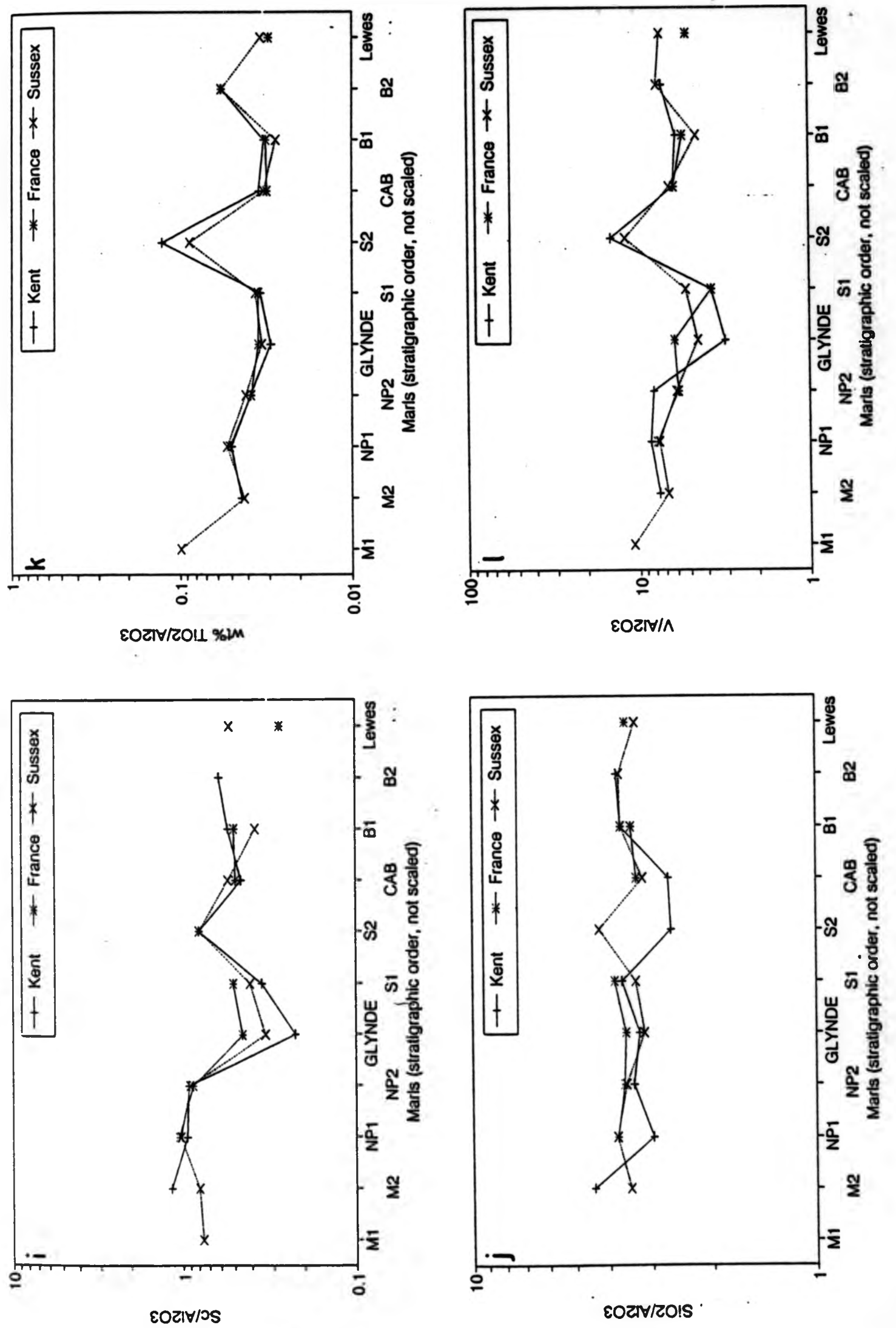
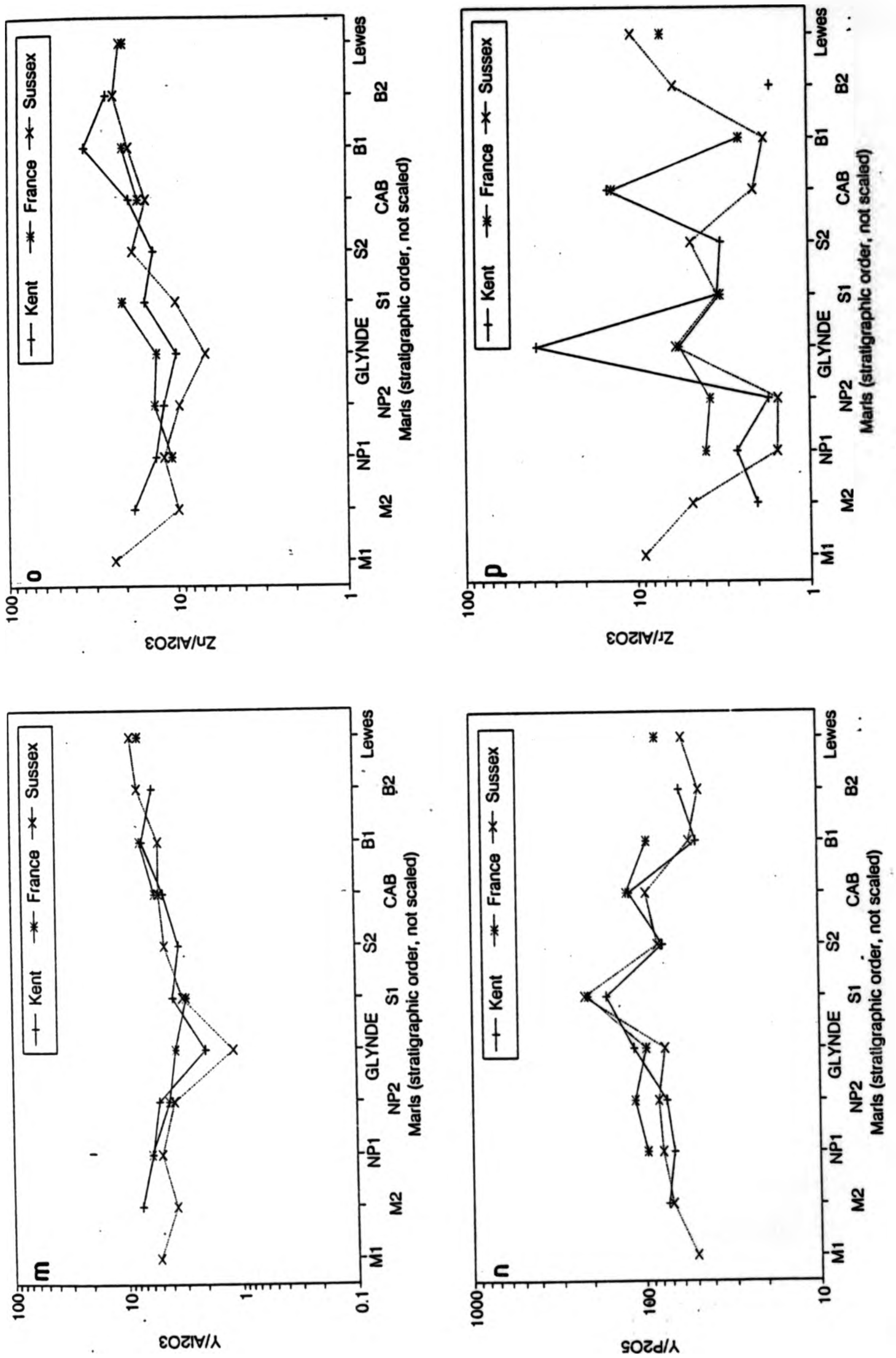


Figure 7.1 cont.



A SUMMARY OF OBSERVED SIMILARITIES BETWEEN KENT, FRANCE AND SUSSEX FOR ALUMINIUM NORMALISED ELEMENTS.

Figure 7.2

	M2	NP1	NP2	G	S1	S2	CAB	B1	B2	L
Ba/Al_2O_3		KS	KS	ks	ks	ks	KS	KF	KS	SF
Fe_2O_3/Al_2O_3	ks	a	SFk	a	a	ks	SFk	A	KS	sf
K_2O/Al_2O_3	ks	KFs	KFs		A	KS	A	KF	ks	SF
Li/Al_2O_3		SF	sf	sf			a	a	KS	sf
MgO/Al_2O_3		a	a	a	a	KS	A	a	KS	SF
Ni/Al_2O_3				A	SF		A			
Sc/Al_2O_3		A	A		a	KS	A	a		
TiO_2/Al_2O_3	KS	A	A	A	A	ks	A	A	KS	SF
V/Al_2O_3	KS	A	SFk		KF	KS	A	A	KS	sf
Y/Al_2O_3		A	A		A	KS	A	KFs	ks	SF
Zn/Al_2O_3		A	a			ks	A	SF	KS	SF
Zr/Al_2O_3			KS	SF	A	ks		sf		sf

Y/P_2O_5	ks	a	a	a	SFk	KS	KFs	KSf	ks	sf

Excellent- Good- correlation between:

KS	ks	Kent and Sussex
KF	kf	Kent and France
SF	sf	Sussex and France
A	a	All

Figure 7.3

MEAN VALUES AND STANDARD DEVIATIONS FOR ALUMINIUM NORMALISED ELEMENTS

Results from Kent, France and Sussex which are similar.

Key:

1. Mean value from all three localities.
2. Standard deviation of the mean from all three localities.
3. Mean value when marl is not present at all three localities, or when one result is anomalous.
4. Standard deviation derived from 3.

	M2	NP1	NP2	G	S1	S2	CAB	B1	B2	L
Ba/Al_2O_3		19·87 ·11 24·5 6·56	17·2 ·51 26·7 13·45	4·34 1·08 13·03 12·3	6·3 ·57 8·89 3·7	14·8 2·49	10·1 ·40 12·03 2·76	9·96 ·003 8·7 1·78	11·43 ·30	8·08 ·60
Fe_2O_3/Al_2O_3	·242 ·023	·247 ·018	·222 ·03	·174 ·018	·216 ·02	·299 ·041	·206 ·02	·237 ·018	·247 ·004	·207 ·015
K_2O/Al_2O_3	·19 ·017	·18 ·012	·166 ·016	·069 ·031	·076 ·004	·168 ·0005	·11 ·006	·111 ·0005 ·091 ·027	·119 ·017	·099 ·004
Li/Al_2O_3		6·19 ·059 7·87 2·37	5·12 ·80	8·92 1·33			12·32 1·5	20·1 1·61	24·03 1·3	23·9 3·5
MgO/Al_2O_3		·316 ·030	·31 ·037	·32 ·045	·219 ·15	·334 ·007	·372 ·013	·513 ·07	·544 ·0005	·529 ·046
Ni/Al_2O_3				2·85 ·17	3·71 ·026 3·29 ·60		2·43 ·22			
Sc/Al_2O_3		·996 ·05	·888 ·026	·334 ·09	·418 ·07	·794 ·0015	·499 ·03	·472 ·07	·609	·403 ·129
TiO_2/Al_2O_3	·043 ·001	·051 ·001	·039 ·001	·033 ·002	·035 ·0008	·107 ·002	·033 ·002	·03 ·002	·057	·032 ·002
V/Al_2O_3	7·20 ·41	7·99 ·413	6·68 1·05	4·6 1·24	3·75 ·008 4·26 ·71	13·09 1·25	6·38 ·16	5·33 ·58	7·50 ·24	6·26 1·09
Y/Al_2O_3		5·61 ·49	4·35 ·56	2·28 1·05	3·29 ·38	3·94 ·56	5·03 ·30	6·38 ·98	6·61 1·0	7·97 ·62
Zn/Al_2O_3		12·0 1·04	11·73 1·6			15·93 2·2	17·17 1·88	19·92 ·77 24·96 7·14	24·5 1·34	20·89·56
Zr/Al_2O_3			1·62 ·105 2·31 ·985	5·74 ·13 16·54 15·3	3·29 ·06	3·96 ·79		2·14 ·34		8·77 1·69

Key:

3	4
1	2

Figure 7.4

A PLOT OF ALUMINIUM NORMALISED SCANDIUM AND VANADIUM VALUES FROM MIDDLE AND UPPER TURONIAN MARLS.

Data from Middle and Upper Turonian marls from Kent, France and Sussex showing intra-marl similarities and inter-marl differences.

Key:

NP1 New Pit Marl 1

NP2 New Pit Marl 2

G Glynde Marl 1 [Caburn]

S1 Southerham Marl 1

S2 Southerham Marl 2

C Caburn Marl

B1 Bridgewick Marl 1

B2 Bridgewick Marl 2

L Lewes

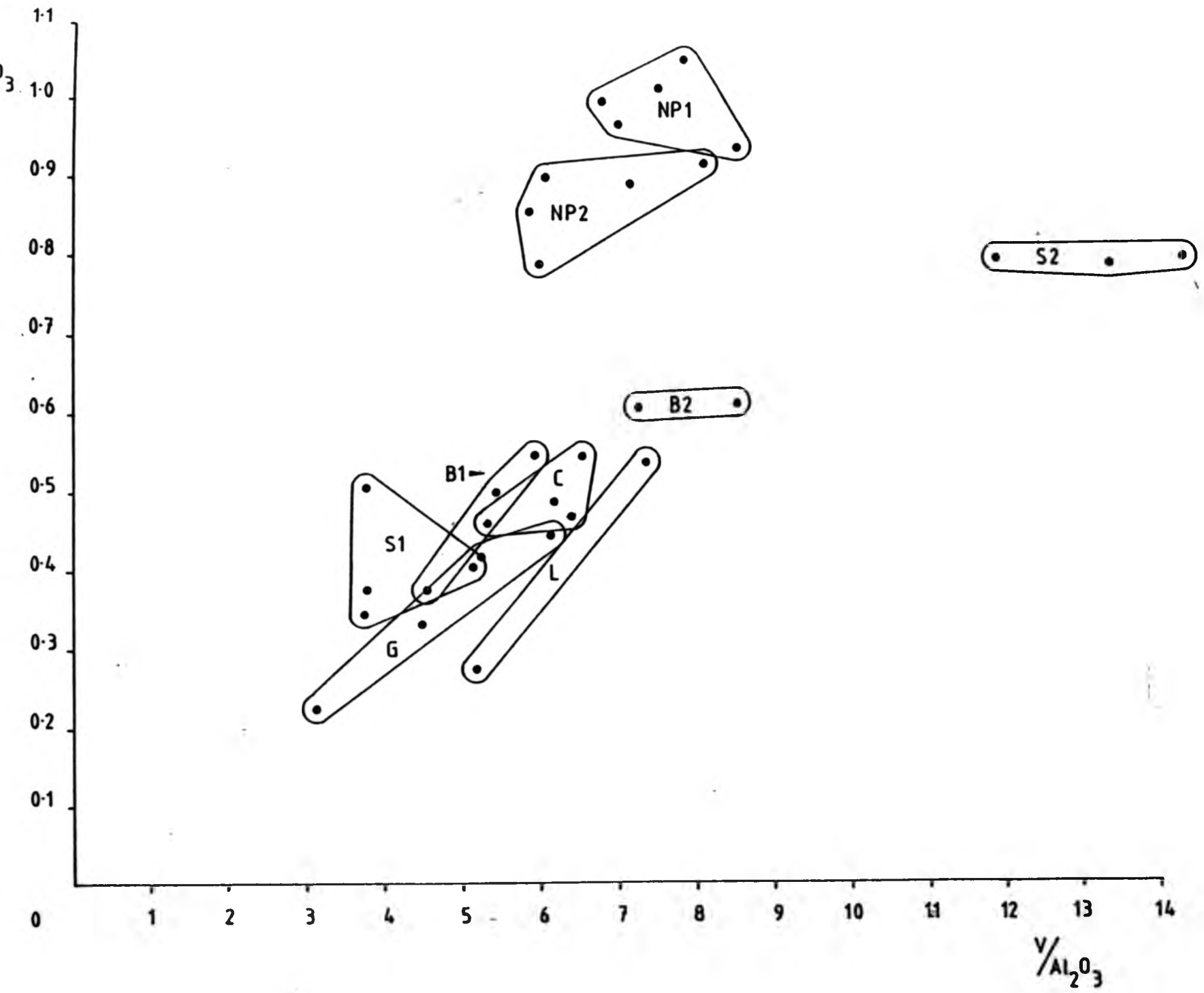

Sc/Al2O3
1·1
1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0
NP1
NP2
S2
B2
B1
C
S1
L
G
1
2
3
4
5
6
7
8
9
10
11
12
13
14
V/Al2O3

Figure 7.5

A PLOT OF ALUMINIUM NORMALISED YTTRIUM AND TITANIUM VALUES FROM MIDDLE AND UPPER TURONIAN MARLS.

Data from Middle and Upper Turonian marls from Kent, France and Sussex showing intra-marl similarities and inter-marl differences.

Key:

NP1 New Pit Marl 1

NP2 New Pit Marl 2

G Glynde Marl 1 [Caburn]

S1 Southerham Marl 1

S2 Southerham Marl 2

C Caburn Marl

B1 Bridgewick Marl 1

B2 Bridgewick Marl 2

L Lewes

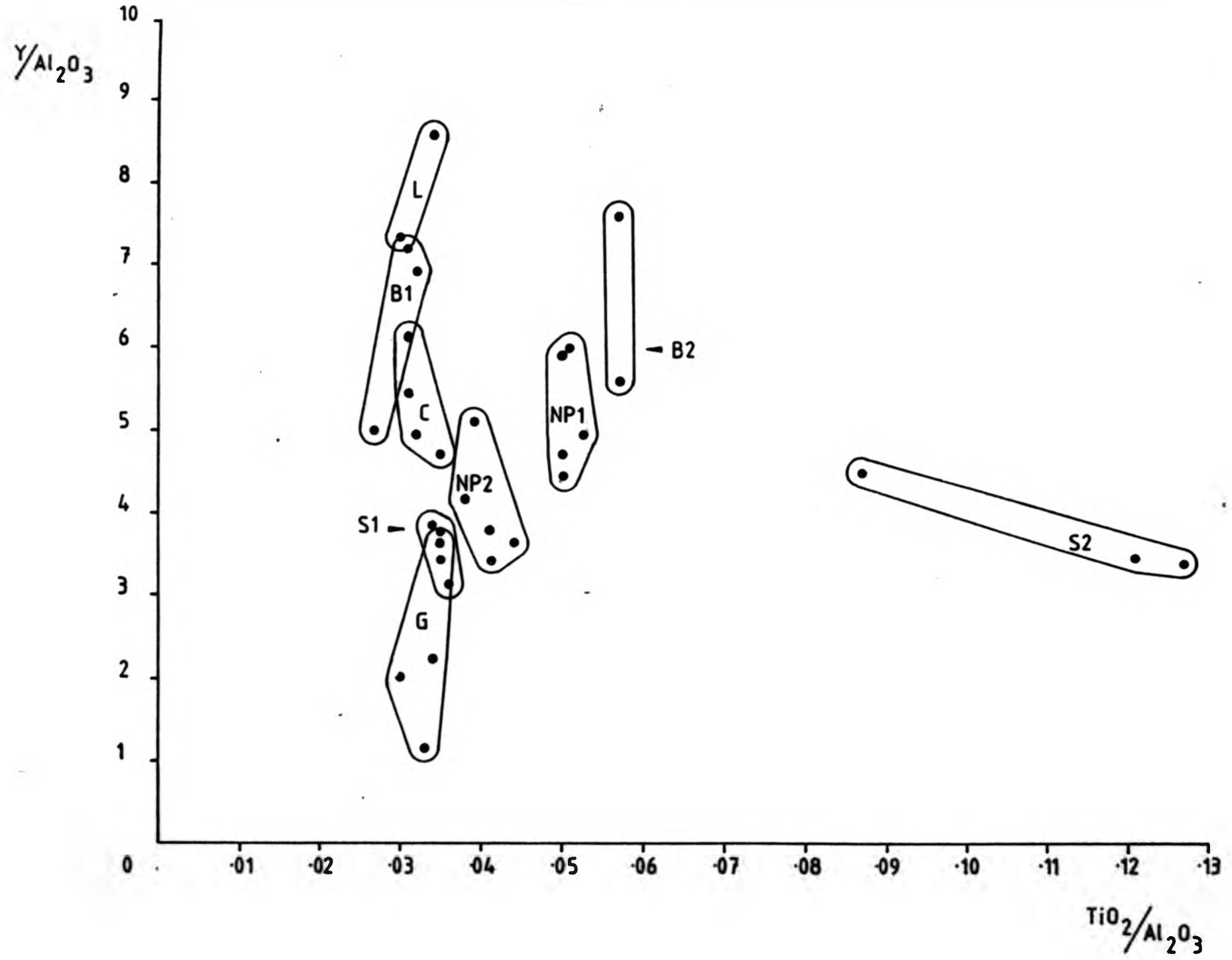

Y/Al2O3
10
9
8
7
6
5
4
3
2
1
0
L
B1
C
NP2
S1
G
NP1
B2
S2
·01
·02
·03
·04
·05
·06
·07
·08
·09
·10
·11
·12
·13
TiO2/Al2O3

Figure 7.6

PLOT OF ALUMINIUM NORMALISED SCANDIUM AND VANADIUM VALUES FROM THE GLYNDE MARLS AT DOVER AND PUYS.

Plots of individual Glynde marls from Dover (D) and Puys, France (P) show the marked difference between the correlateable marl [Dover 2], [Puys 1] and the higher marls. The similarity between the higher Glynde Marls and the New Pit Marls is clearly illustrated.

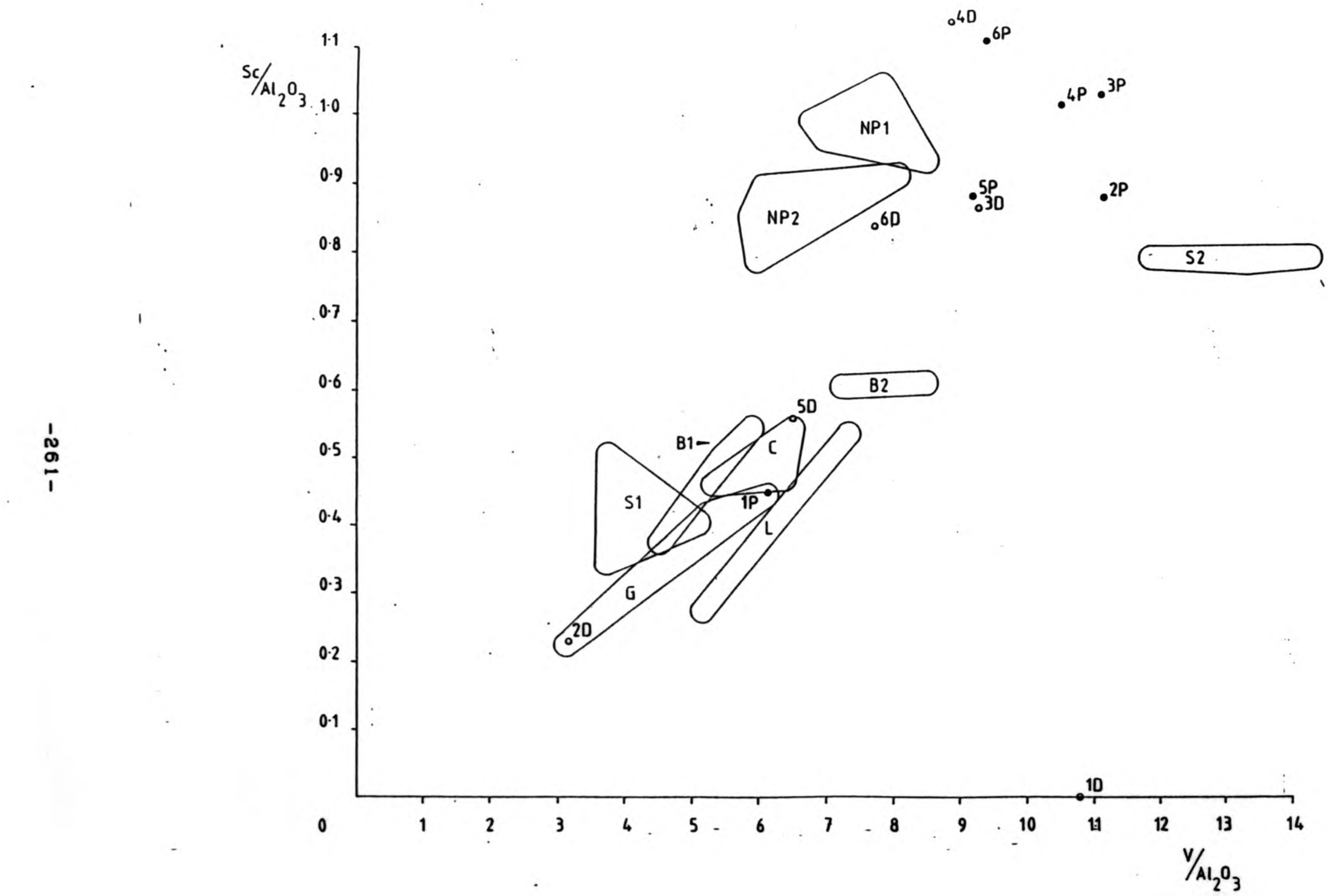
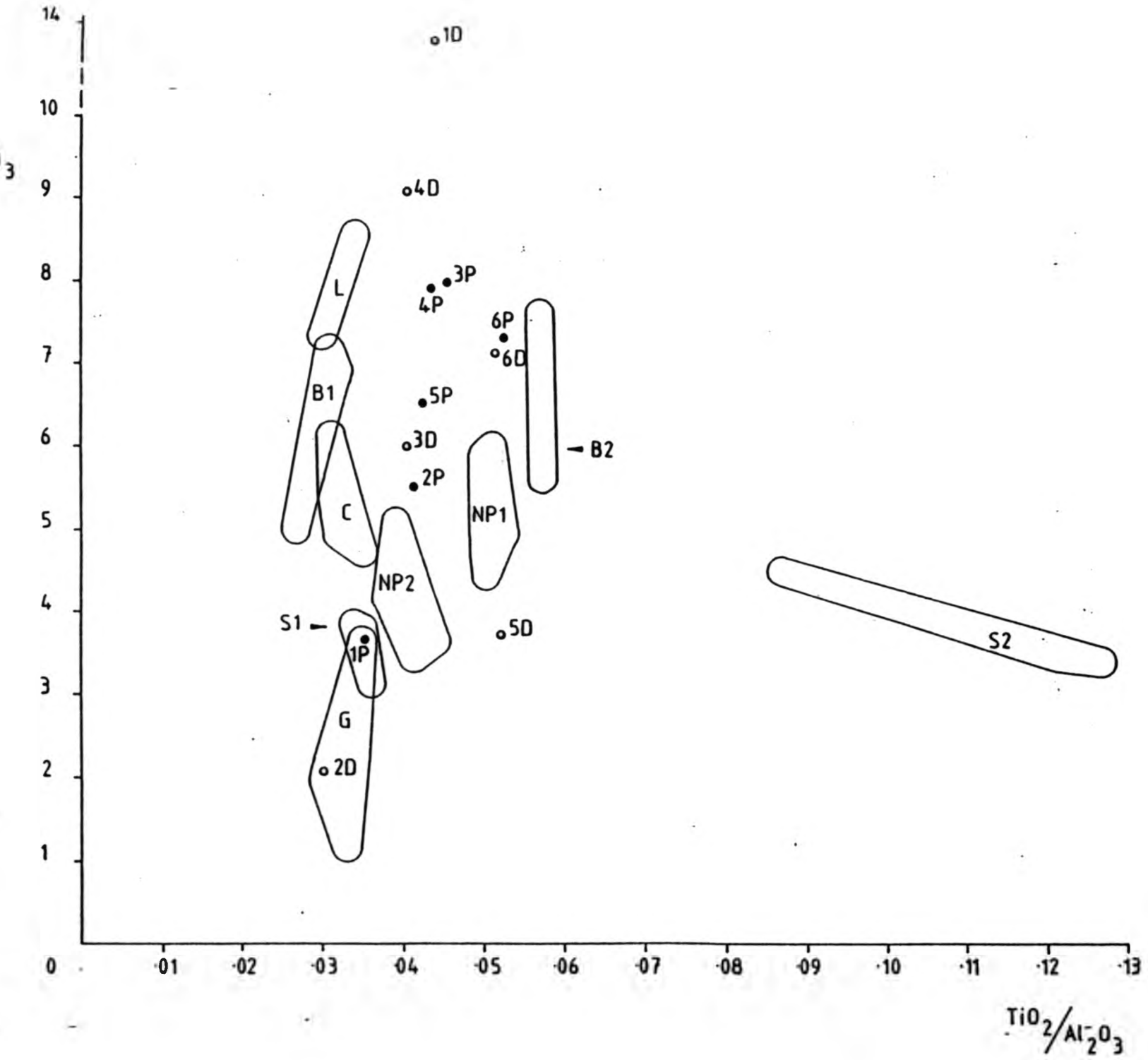

Sc/Al2O3
1·1
1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
V/Al2O3
4D
6P
4P
3P
NP1
NP2
5P
3D
6D
2P
S2
B2
5D
B1
C
S1
1P
L
G
2D
1D

Figure 7.7

PLOT OF ALUMINIUM NORMALISED YTTRIUM AND TITANIUM VALUES FROM THE GLYNDE MARLS AT DOVER AND PUYS.

Plots of individual Glynde marls from Dover (D) and Puys, France (P) show the marked difference between the correlateable marl [Dover 2], [Puys 1] and the higher marls. The similarity of titanium values between the higher Glynde Marls and the New Pit Marls is well illustrated.


Y/Al2O3
TiO2/Al2O3
14
10
9
8
7
6
5
4
3
2
1
0
·01
·02
·03
·04
·05
·06
·07
·08
·09
·10
·11
·12
·13
1D
4D
3P
4P
6P
6D
5P
3D
2P
5D
1P
2D
L
B1
C
NP2
S1
G
NP1
B2
S2

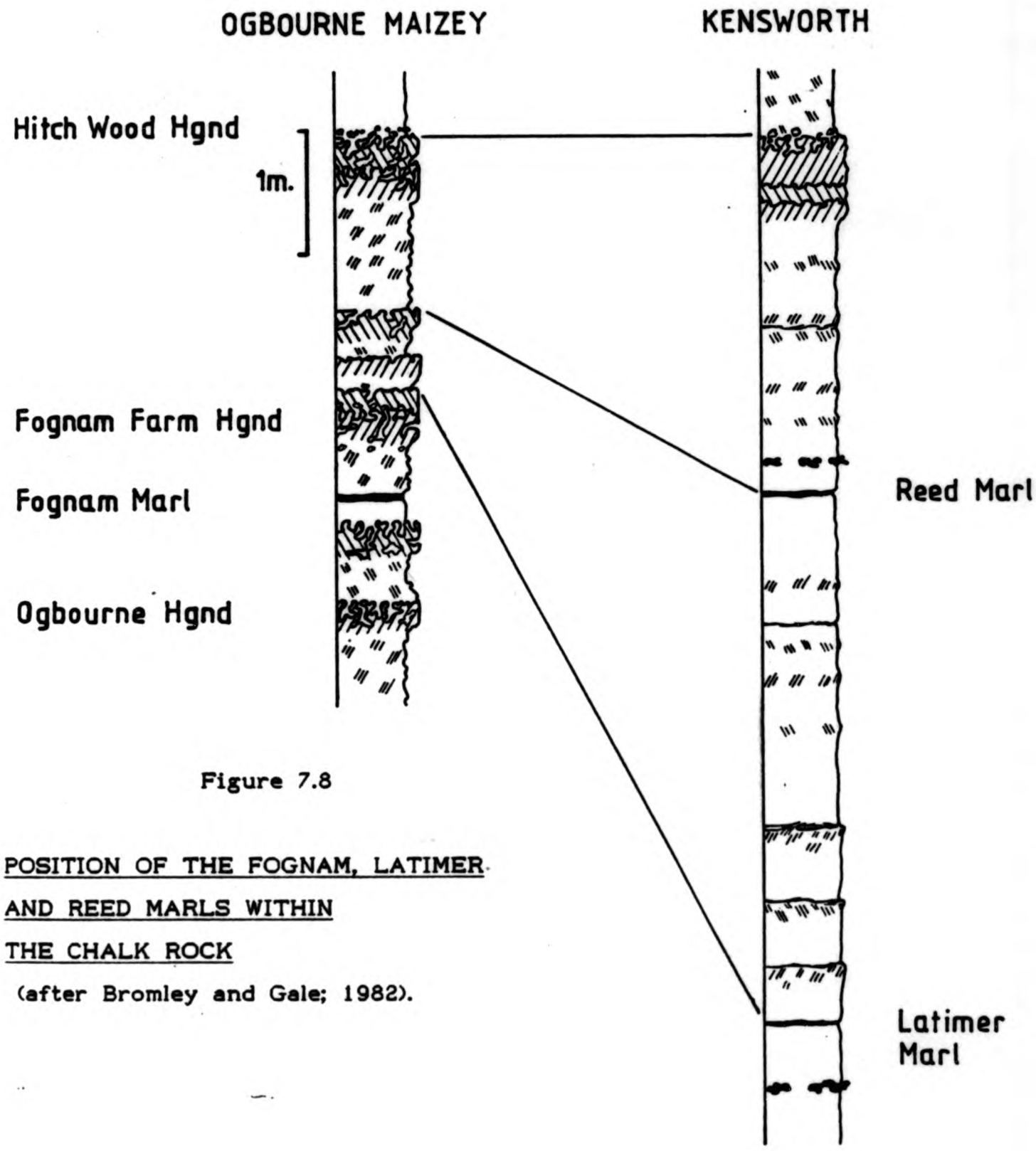


Figure 7.8

POSITION OF THE FOGNAM, LATIMER AND REED MARLS WITHIN THE CHALK ROCK

(after Bromley and Gale; 1982).

Figure 7.9

PLOTS OF ALUMINIUM NORMALISED SCANDIUM AND VANADIUM RESULTS FROM MARLS ASSOCIATED WITH THE CHALK ROCK

See text for key to individual plots.

KEY

● Beggars Knoll

▲ Kensworth

△ Ewelme

▼ Burghclere

▽ Fognam Farm

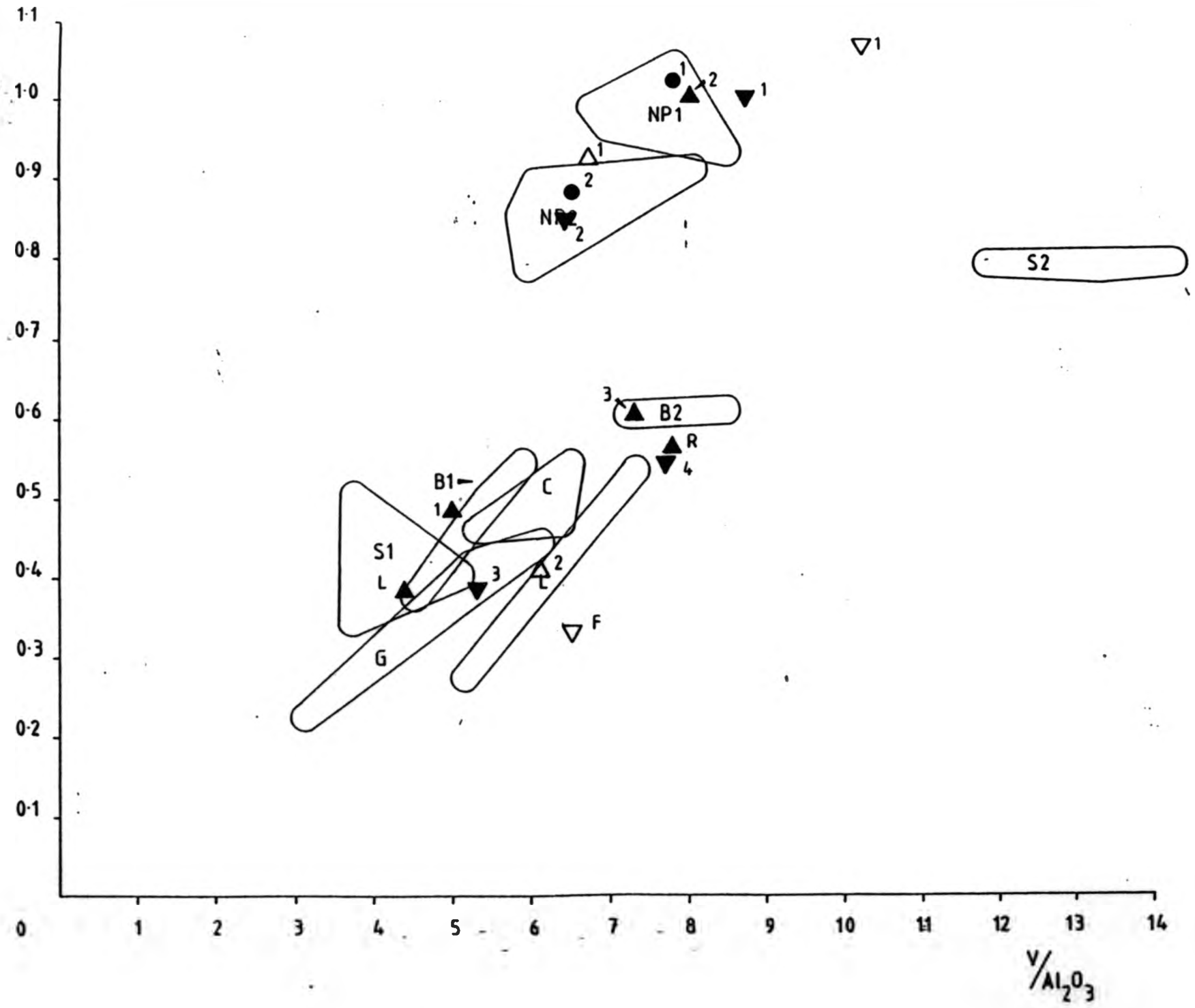

Sc/Al2O3
1·1
1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
V/Al2O3
NP1
NP2
S2
B2
R
B1
C
S1
L
G
F

Figure 7.10

PLOTS OF ALUMINIUM NORMALISED YTTRIUM AND TITANIUM RESULTS FROM MARLS ASSOCIATED WITH THE CHALK ROCK

See text for key to individual plots.

KEY

● Beggars Knoll

▲ Kensworth

△ Ewelme

▼ Burghclere

▽ Fognam Farm

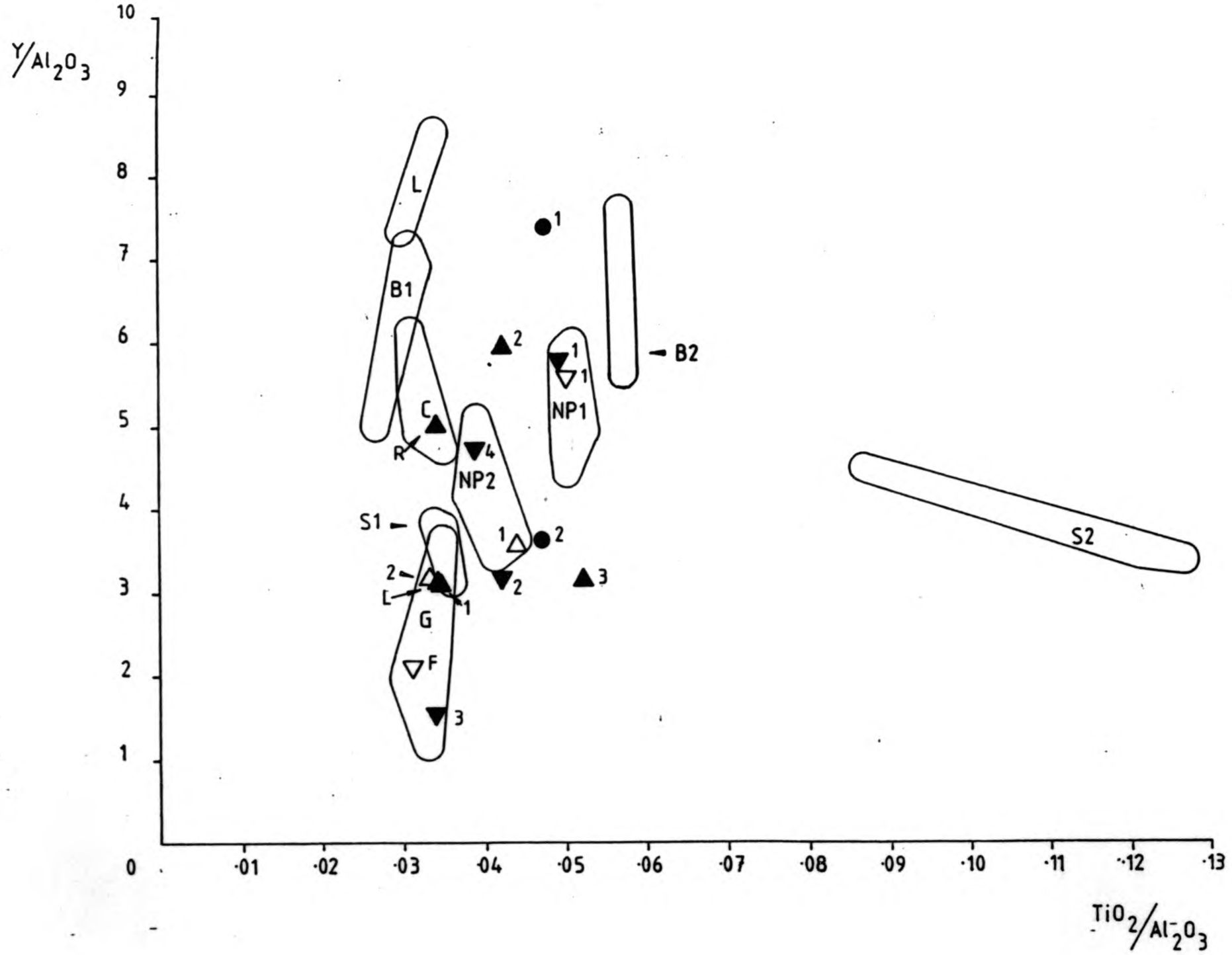

Y/Al2O3
10
9
8
7
6
5
4
3
2
1
0
·01
·02
·03
·04
·05
·06
·07
·08
·09
·10
·11
·12
·13
TiO2/Al2O3
L
B1
B2
C
R
NP1
NP2
S1
S2
G
F
L
1
2
3
4

Figure 7.11

PLOTS OF ALUMINIUM NORMALISED SCANDIUM AND VANADIUM
RESULTS FROM MARLS ASSOCIATED WITH THE SPURIOUS CHALK ROCK

See text for key to individual plots.

KEY

□ Military Road and Compton Bay I.O.W.

○ Shillingstone Hill

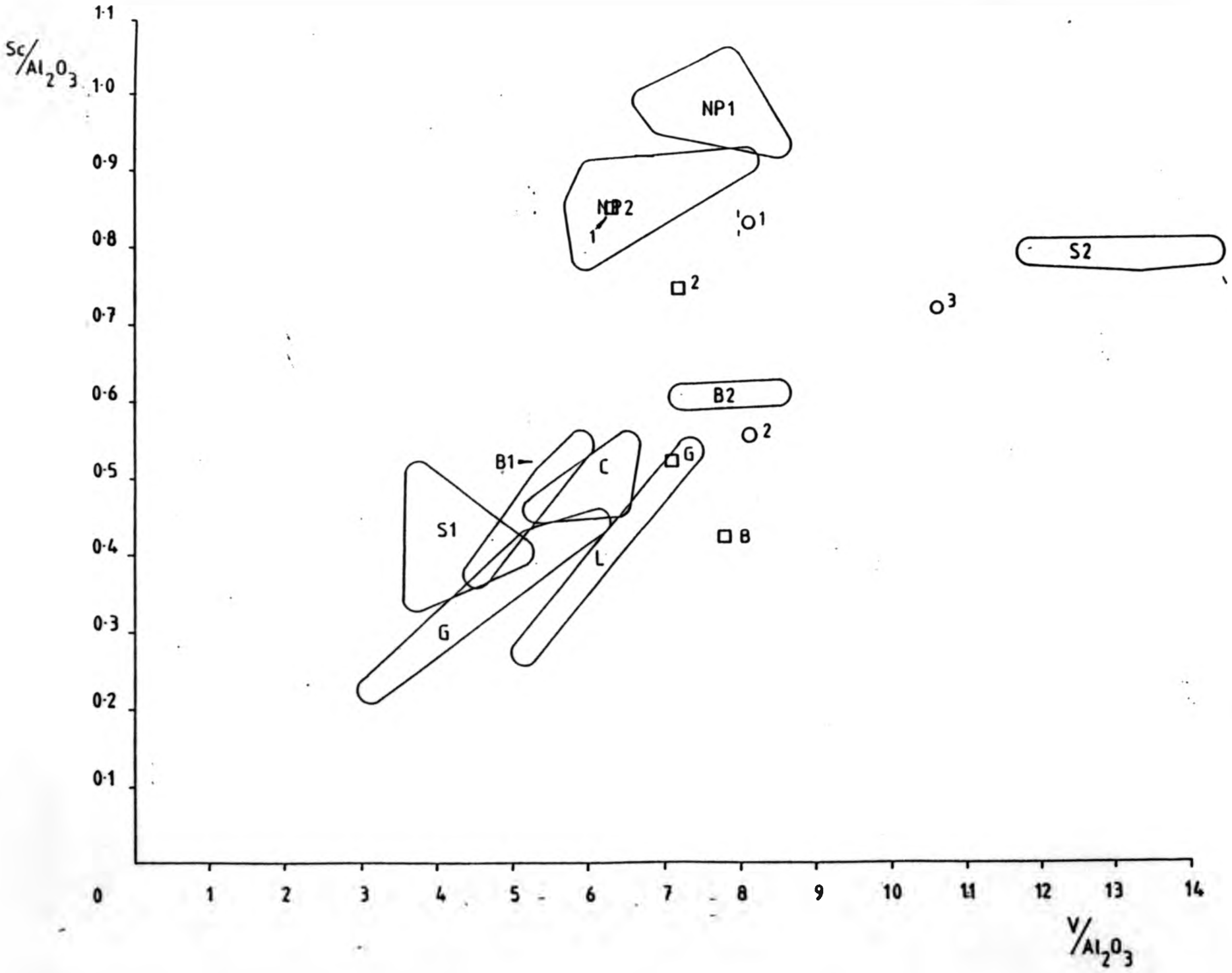

Sc/Al2O3
1·1
1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
V/Al2O3
NP1
NP2
1
2
S2
3
B2
2
B1
C
G
S1
L
G
B

Figure 7.12

PLOTS OF ALUMINIUM NORMALISED YTTRIUM AND TITANIUM
RESULTS FROM MARLS ASSOCIATED WITH THE SPURIOUS CHALK ROCK

See text for key to individual plots.

KEY

□ Military Road and Compton Bay I.O.W.

○ Shillingstone Hill

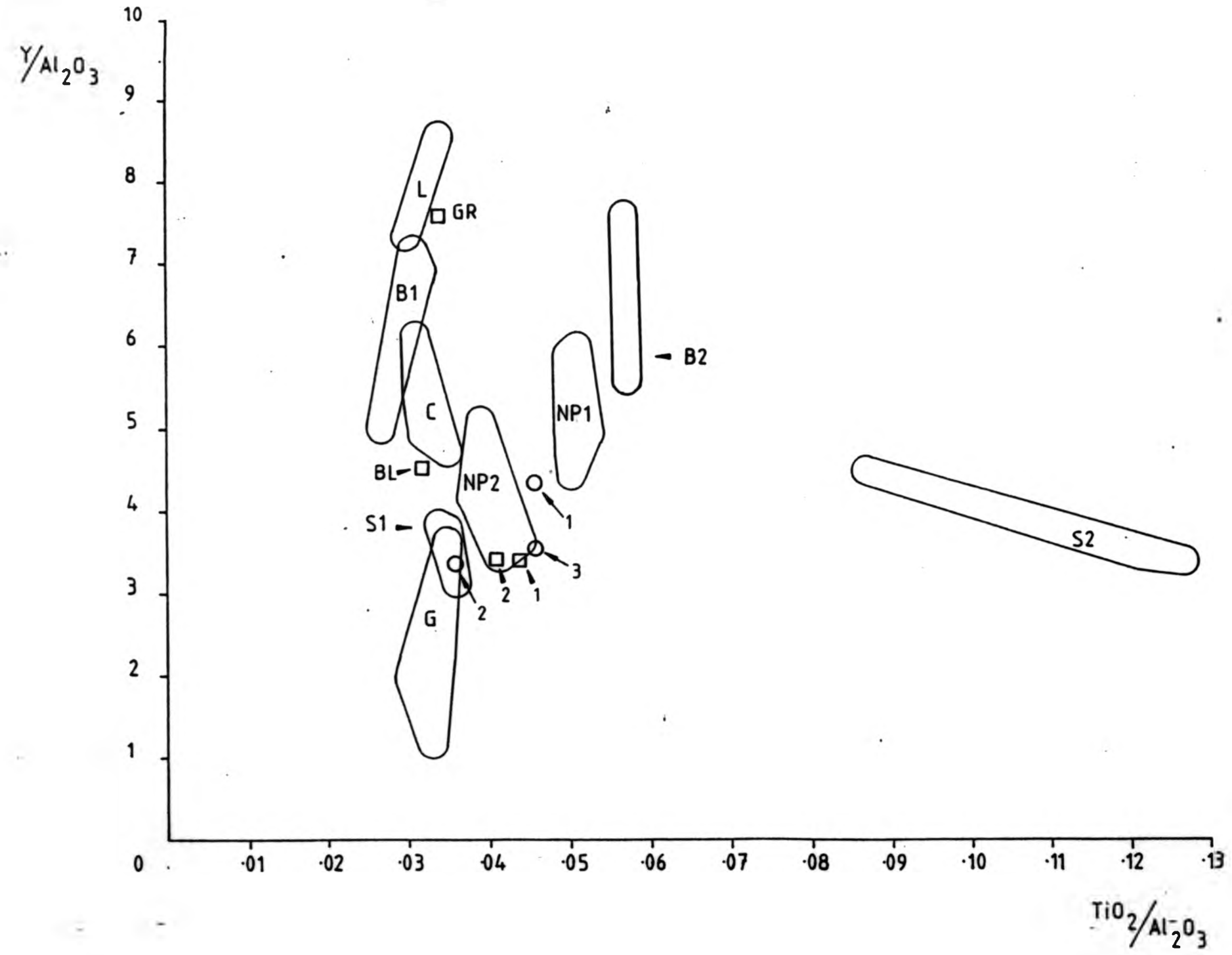

Y/Al2O3
10
9
8
7
6
5
4
3
2
1
0
·01
·02
·03
·04
·05
·06
·07
·08
·09
·10
·11
·12
·13
TiO2/Al2O3
L
GR
B1
C
BL
NP2
S1
G
NP1
B2
S2
1
2
3
2
1
2

Figure 7.13

SUMMARY OF THE CORRELATION BETWEEN SUSSEX, THE CHALK ROCK AND THE SPURIOUS CHALK ROCK

Note the difference in scale of the Sussex section. The dashed marls at the base of Ewelme and Kensworth have not been observed, but are assumed to be present. The question marks between Beggars Knoll, Shillingstone and the Isle of Wight indicate the correlation is slightly tentative (see text).

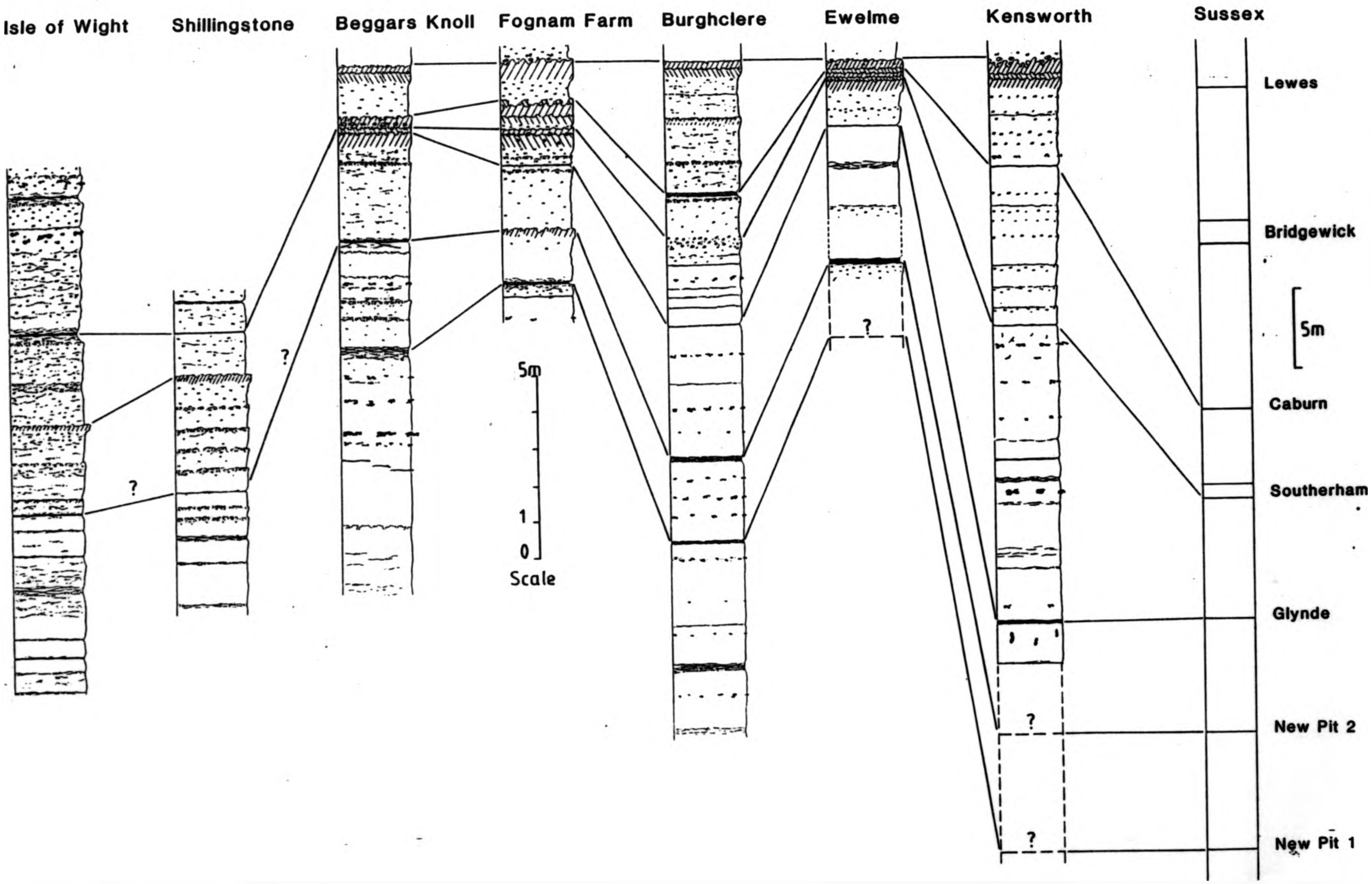

Isle of Wight
Shillingstone
Beggars Knoll
Fognam Farm
Burghclere
Ewelme
Kensworth
Sussex
Lewes
Bridgewick
Caburn
Southerham
Glynde
New Pit 2
New Pit 1
5m
Scale
1
0
?

Figure 7.14

DIAGRAM SHOWING THE INCREASE IN CONDENSATION OCCURING ALONG A TRANSECT FROM THE ANGLO-PARIS BASIN ONTO THE LONDON PLATFORM

Note the difference in scale between Kent and Sussex and the other four sections.

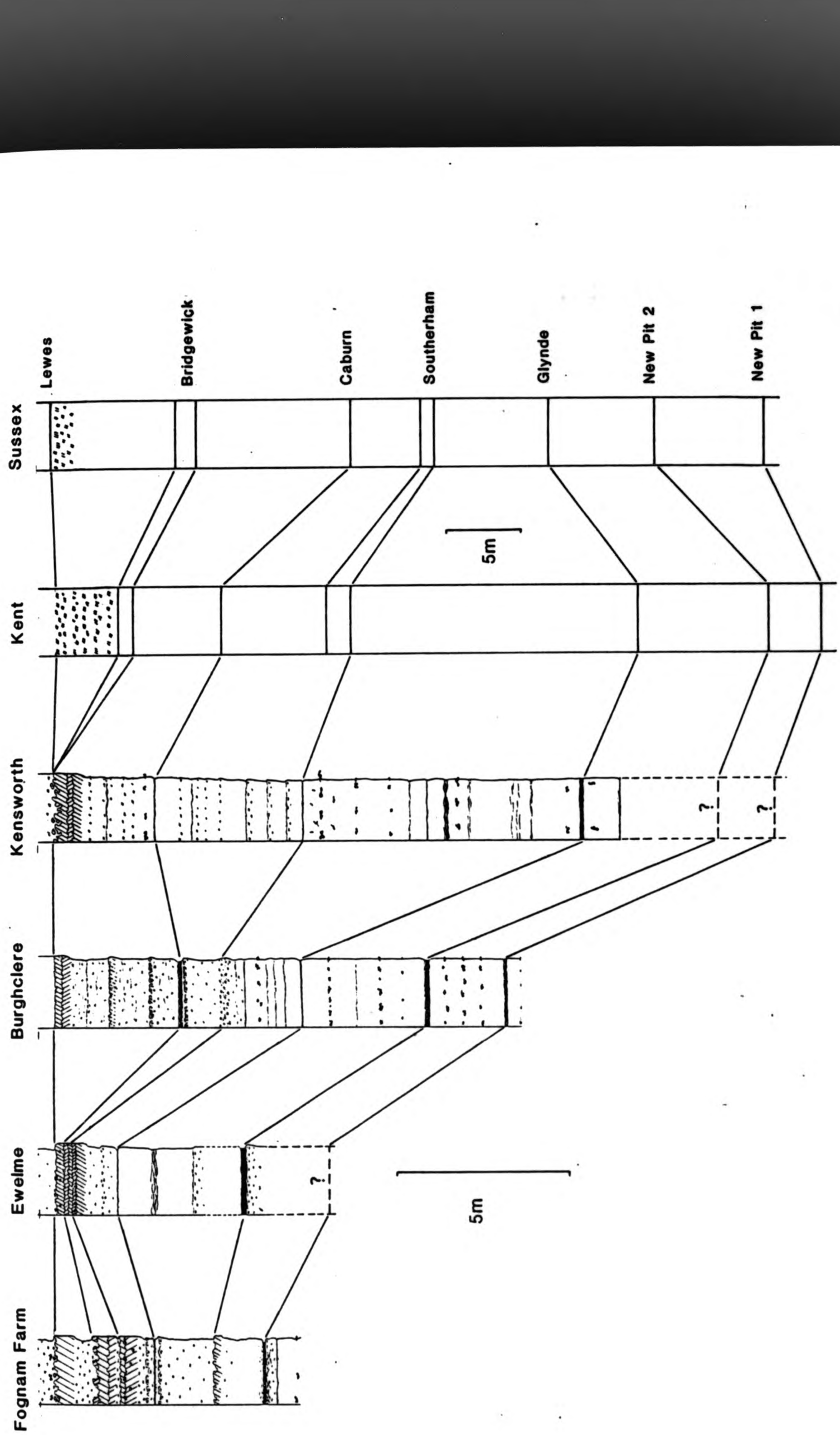

Sussex
Lewes
Bridgewick
Caburn
Southerham
Glynde
New Pit 2
New Pit 1
5m
Kent
Kensworth
?
?
Burghclere
Ewelme
?
5m
Fognam Farm

Figure 7.15

POSITION OF PRE-PERMIAN FAULTS AND BASINS, AND THE POSITION OF THE MID-DORSET SWELL.

Included on the map are the Chalk Rock and Spurious Chalk Rock localities mentioned in the text (after Whittaker, 1985).

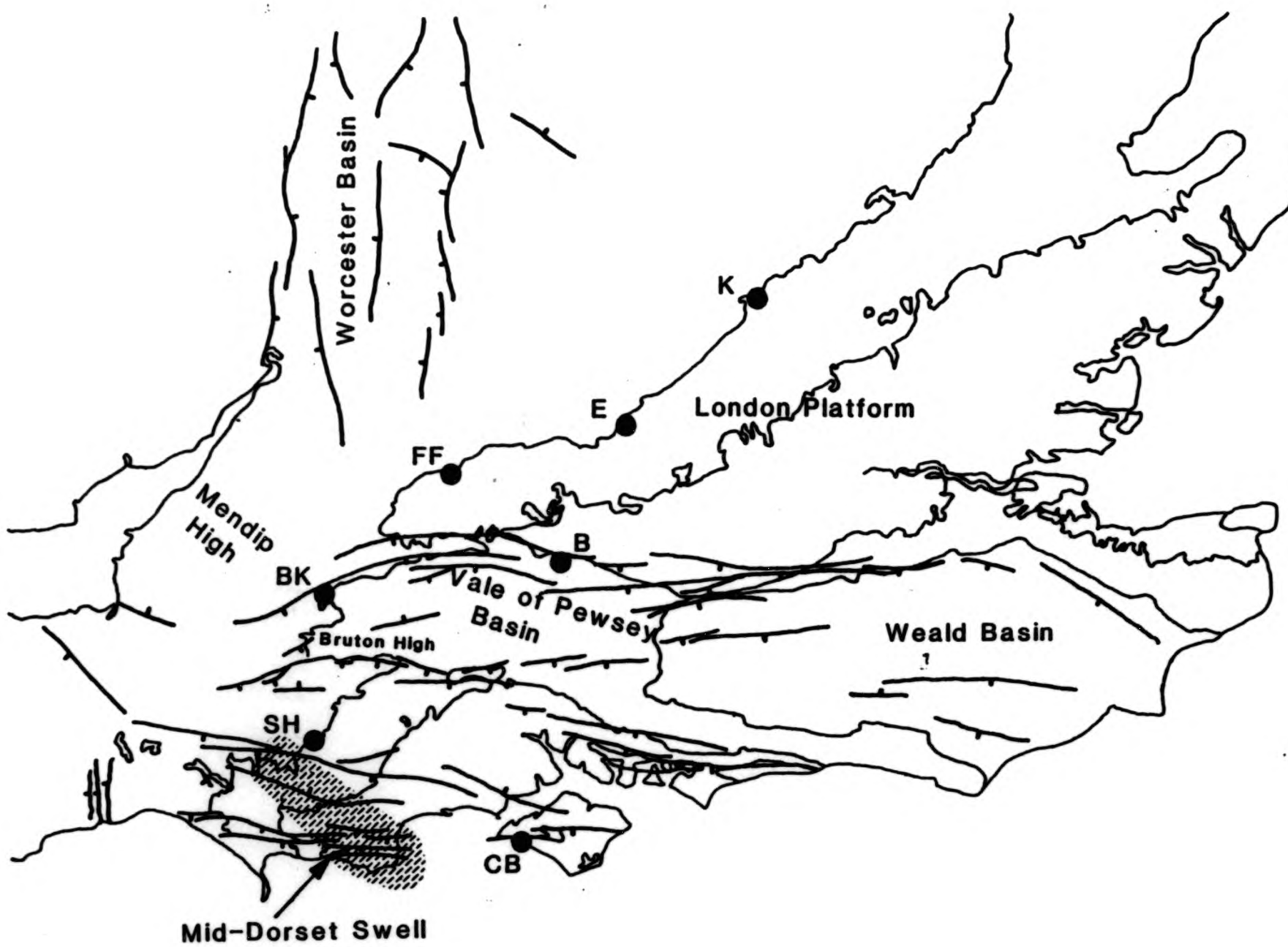

Worcester Basin
K
E
London Platform
FF
Mendip High
B
BK
Vale of Pewsey Basin
Bruton High
Weald Basin
SH
CB
Mid-Dorset Swell

Figure 7.16

PLOTS OF ALUMINIUM NORMALISED SCANDIUM AND VANADIUM RESULTS FROM THE NORTHERN PROVINCE

The points are plotted against the areas occupied by Middle and Upper Turonian marls from the Anglo-Paris Basin.

KEY

△ Grasby Marl

▲ Croxton Marl

▽ Barton Marls

▼ Melton Ross Marl

□ Riby Marl

■ Deepdale Marls

○ Beacon Hill Marl

+ Boundary marl between Burnham and Welton

● North Ormsby Marl

Δ Thornton Curtis Marl

▲ Wootton Marls

∇ Ulceby Marl

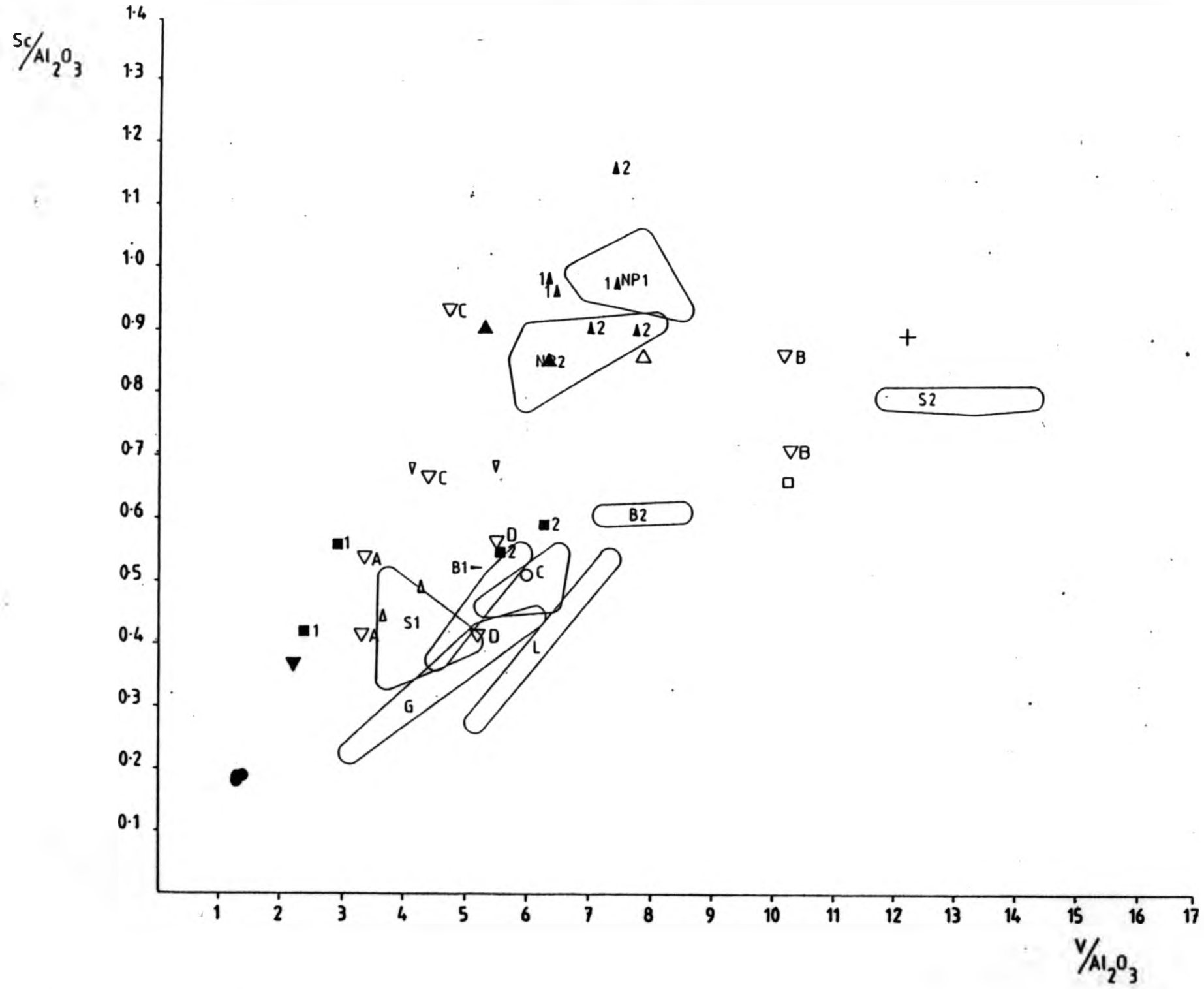

Sc/Al2O3
1·4
1·3
1·2
1·1
1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
V/Al2O3
A2
1A
1 A NP1
∇C
A2
A2
N A2
∇B
S2
∇B
∇C
∇C
B2
■1
∇A
■2
∇D
■2
B1
C
Δ
Δ
S1
■1
∇A
∇D
L
G

Figure 7.17

PLOTS OF ALUMINIUM NORMALISED YTTRIUM AND TITANIUM RESULTS FROM THE NORTHERN PROVINCE

The points are plotted against the areas occupied by Middle and Upper Turonian marls from the Anglo-Paris Basin.

KEY

△ Grasby Marl

▲ Croxton Marl

▽ Barton Marls

▼ Melton Ross Marl

□ Riby Marl

■ Deepdale Marls

○ Beacon Hill Marl

+ Boundary marl between Burnham and Welton

● North Ormsby Marl

Δ Thornton Curtis Marl

▲ Wootton Marls

▽ Ulceby Marl

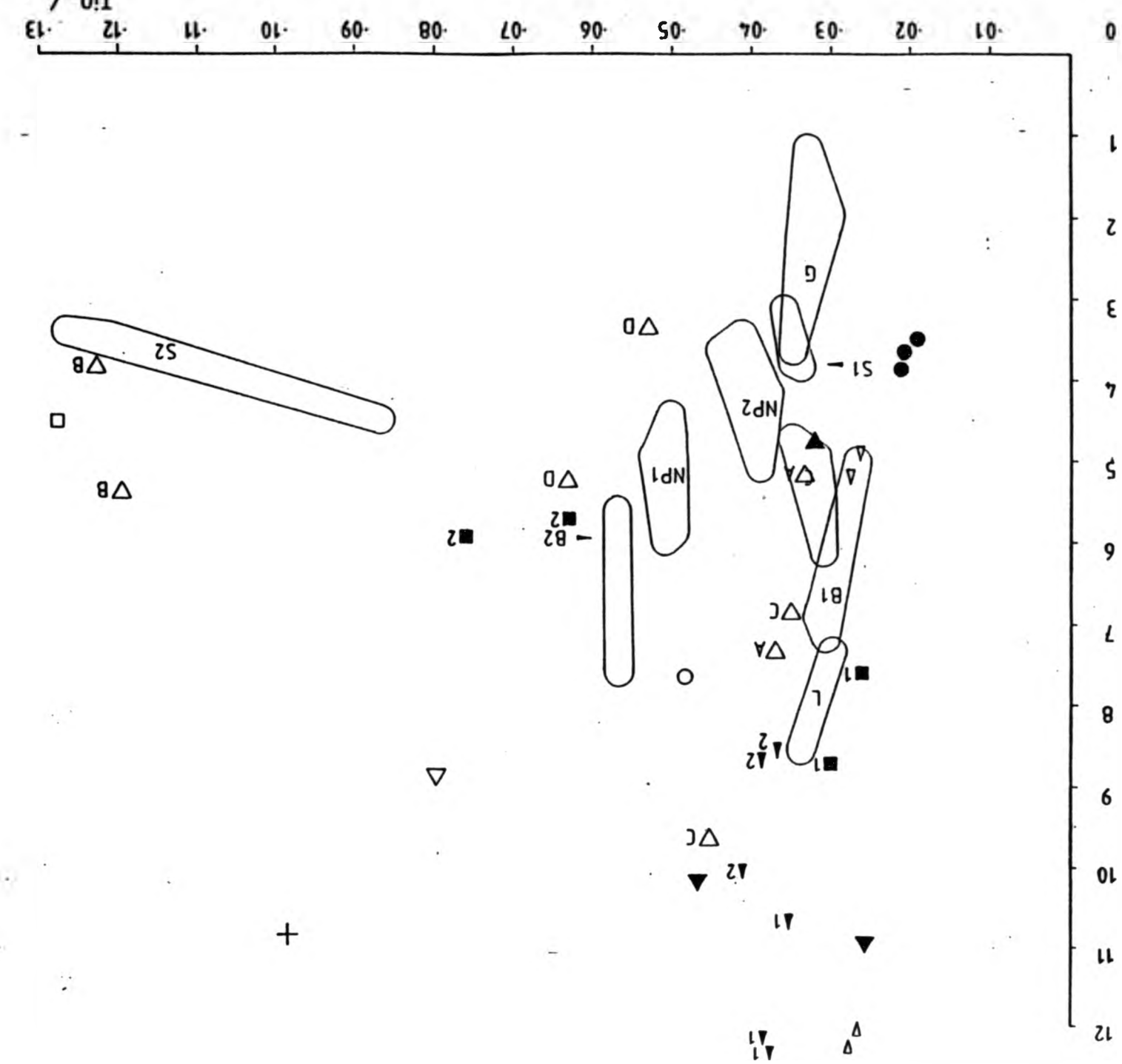

TiO_2/Al_2O_3
Y/Al_2O_3
S2
S1
G
NP2
NP1
A
B1
B2
L

Figure 7.18

A SUMMARY OF THE PROPOSED NORTHERN PROVINCE - ANGLO-PARIS BASIN GEOCHEMICAL CORRELATION

The correlation proposed in this thesis shows marked differences to that proposed by Mortimore and Wood (1986).

Key:

SOUTHERN ENGLAND		NORTHERN PROVINCE	
NP1	New Pit Marl 1	G	Grasby Marl
NP2	New Pit Marl 2	C	Croxton Marl
G	Glynde	BA, BB, BC, BD	Barton Marls
S1	Southerham Marl 1	MR	Melton Ross Marl
S2	Southerham Marl 2	R	Riby Marl
C	Caburn Marl	DL, DU	Deepdale Marls
B1	Bridgewick Marl 1	BH	Beacon Hill Marl
B2	Bridgewick Marl 2	B	Boundary marl
L	Lewes Marl	NO	North Ormsby Marl
		TC	Thornton Curtis Marl
		W	Wootton Marls
		U	Ulceby Marl

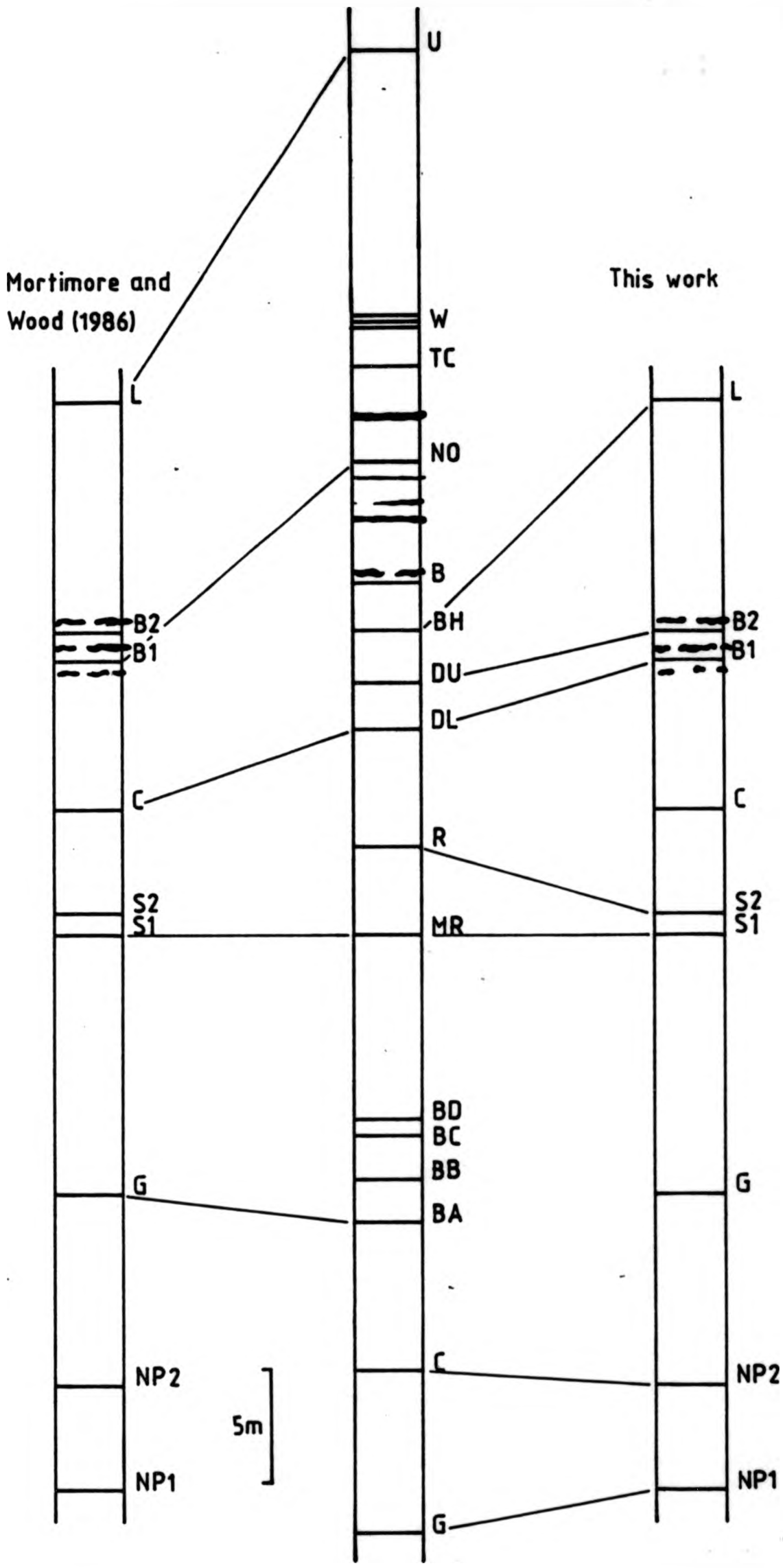

Mortimore and
Wood (1986)
This work
U
W
TC
L
NO
B
B2
BH
B1
DU
DL
C
R
S2
S1
MR
BD
BC
BB
G
BA
NP2
5m
NP1
C
G

Figure 8.1

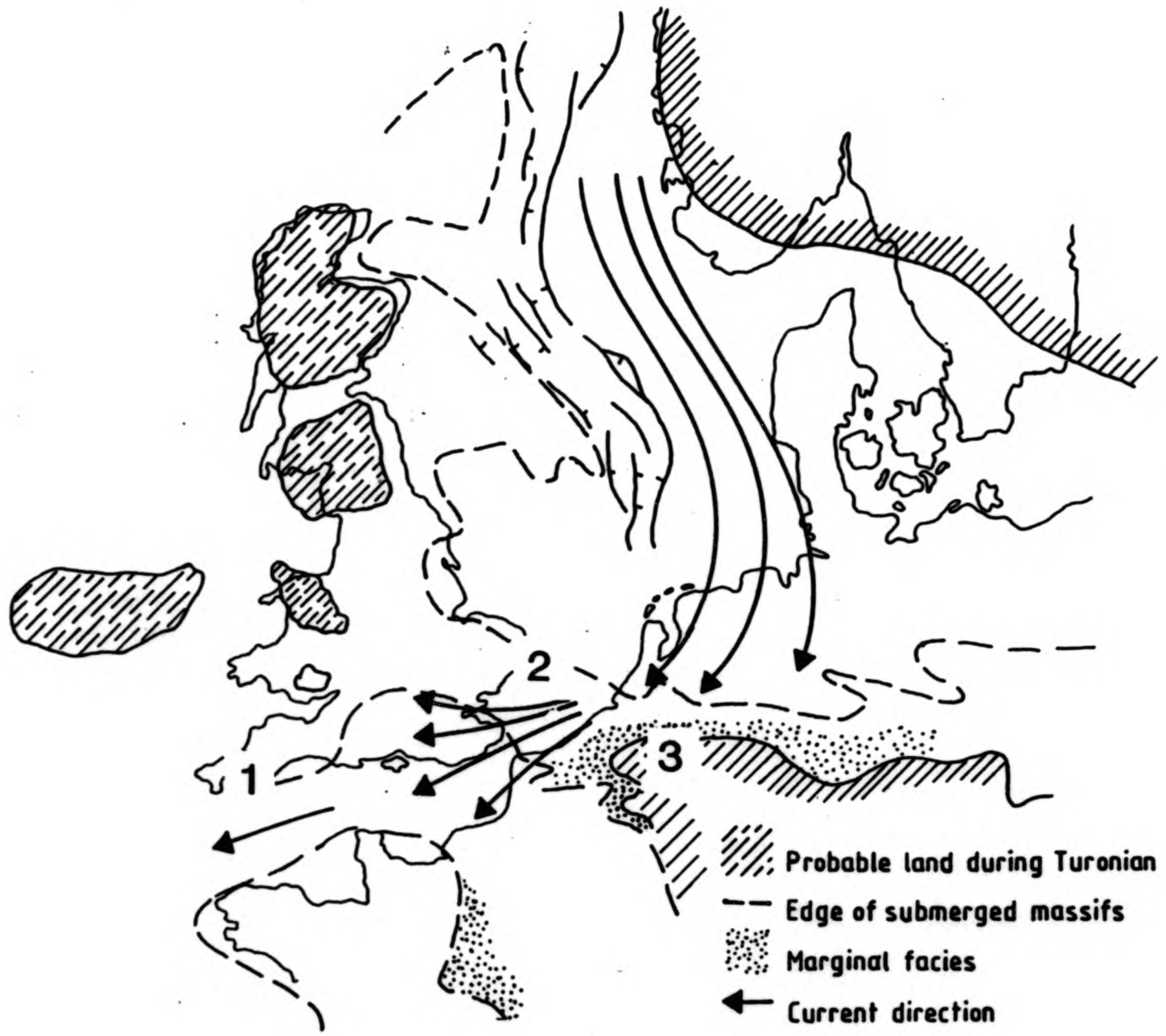
A MODEL TO EXPLAIN THE FORMATION OF MARL BANDS IN THE ANGLO-PARIS BASIN

1. A sharp eustatic fall in sea level results in warm water flowing out of the Anglo-Paris Basin into the Atlantic.

2. The fall in sea level causes changes in current patterns and allows cooler northern water to enter the Anglo-Paris Basin across the London-Brabant High.

3. Whilst crossing the high the cooler water erodes and transports marginal clay deposits from the edge of the Ardennes and deposits them as discrete beds within the Anglo-Paris Basin, forming marl bands.

Palaeogeography from Hancock (1984) and Ernst *et al.* (1983). North Sea current patterns from Ernst *et al.* (1983).


1
2
3
Probable land during Turonian
Edge of submerged massifs
Marginal facies
Current direction

FIGURES TO ACCOMPANY APPENDIX 2

A2.1 Malling Street Marls

A2.2 New Pit Marl 1

A2.3 New Pit Marl 2

A2.4 Glynde Marls

A2.5 Southerham Marls

A2.6 Caburn Marl

A2.7 Bridgewick Marls

A2.8 Lewes Marl

Figure A2.1: Malling Street Marls

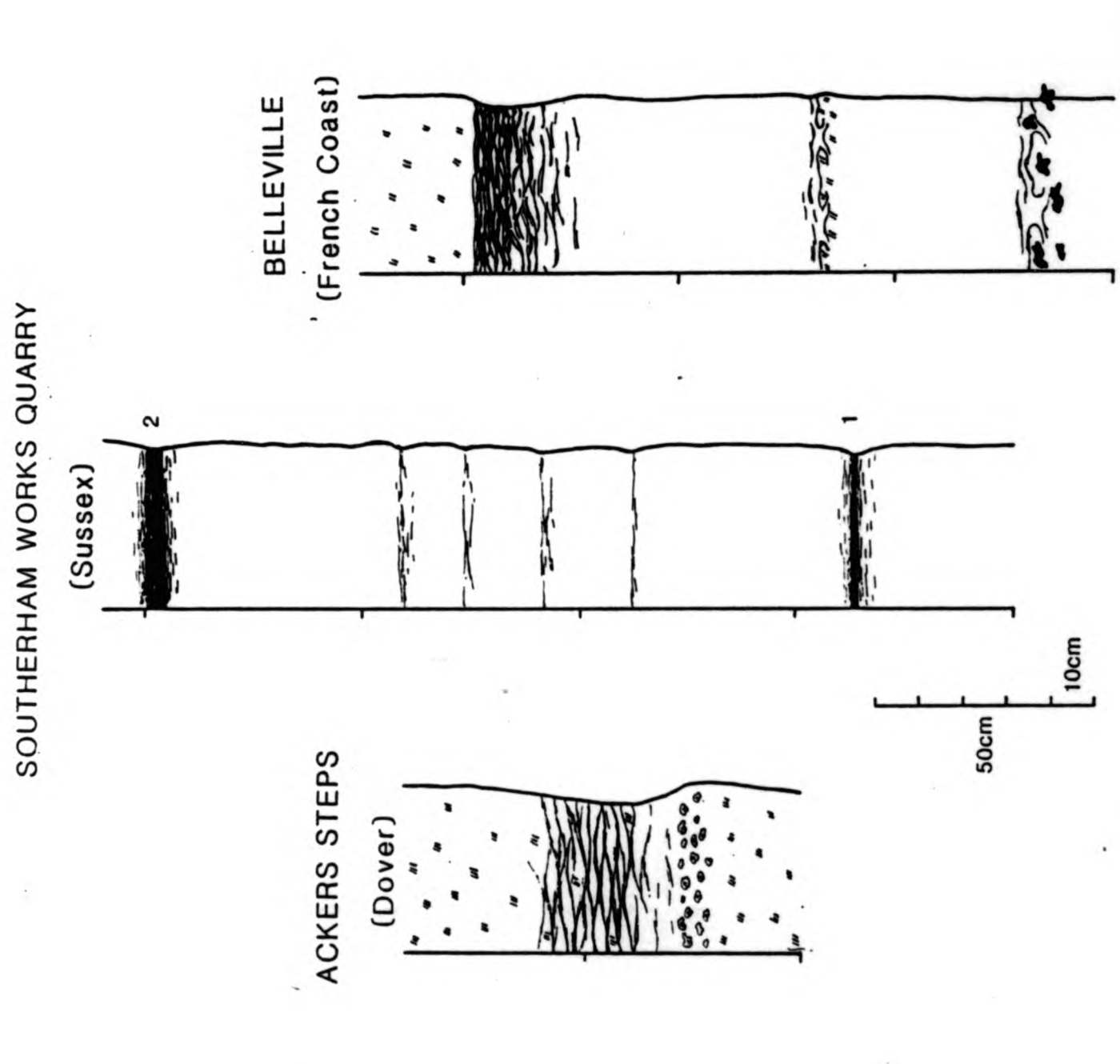
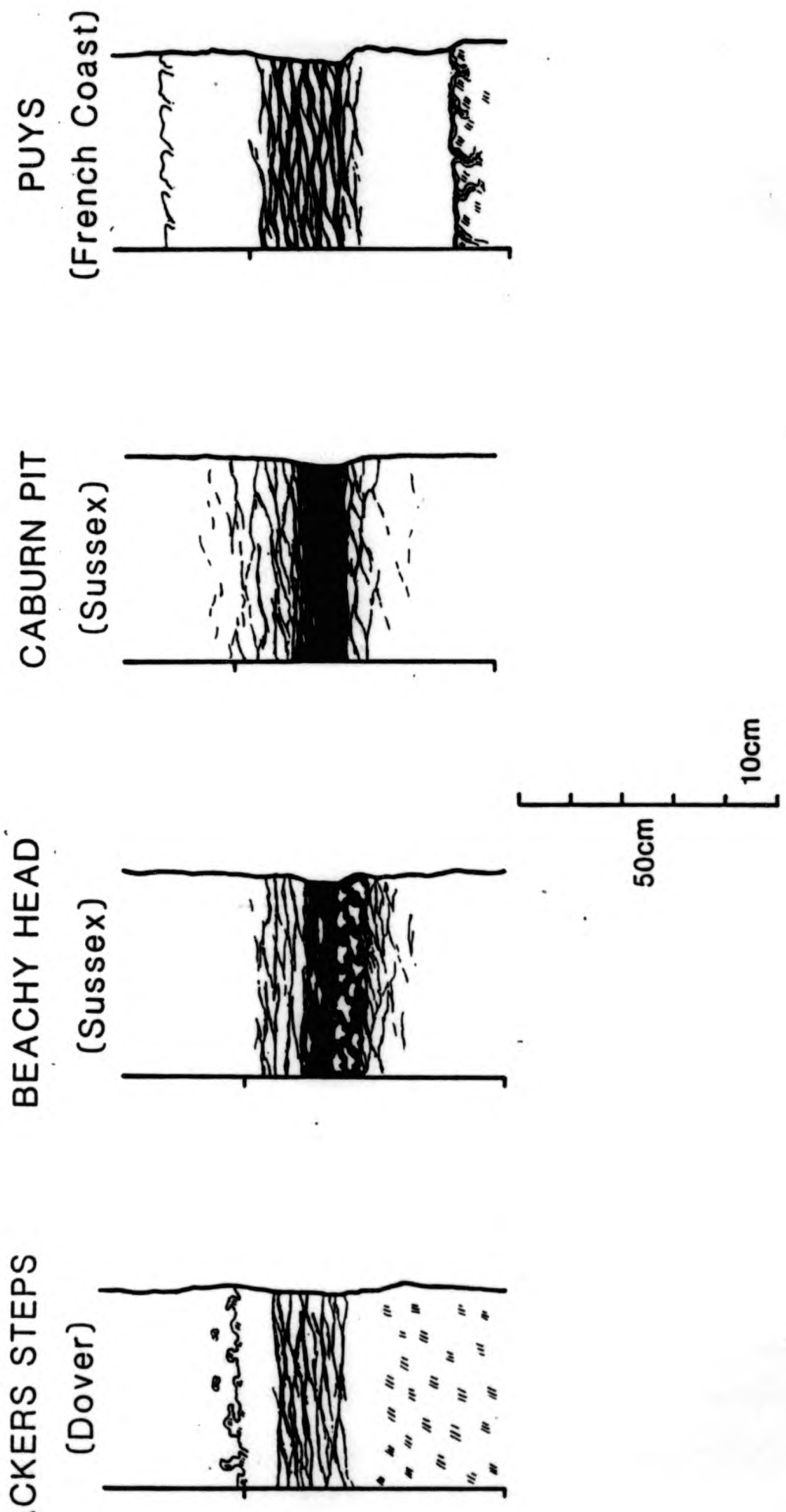


Figure A2.2: New Pit Marl 1



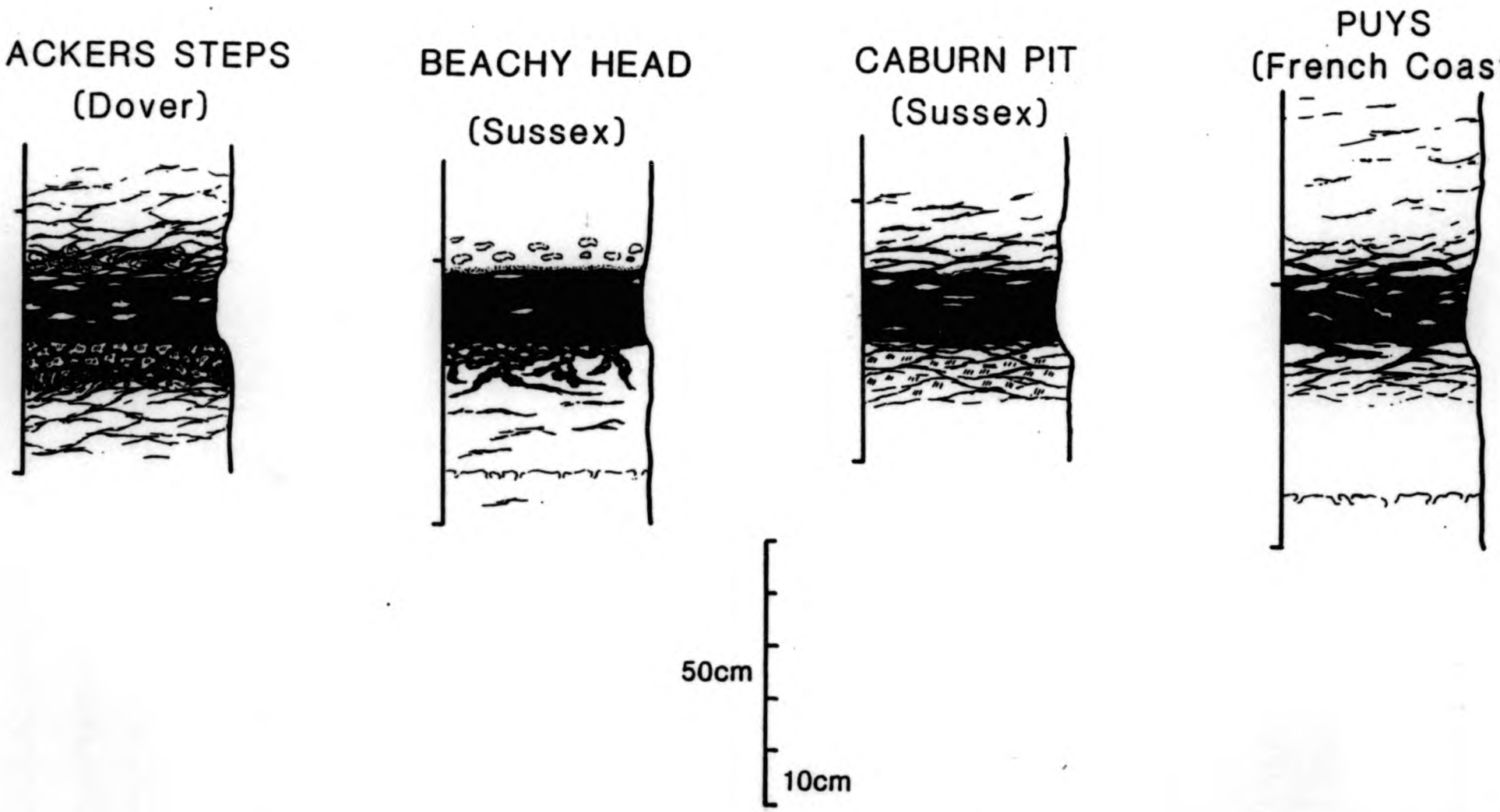


Figure A2.3: New Pit Marl 2

Figure A2.4: Glynde Marls

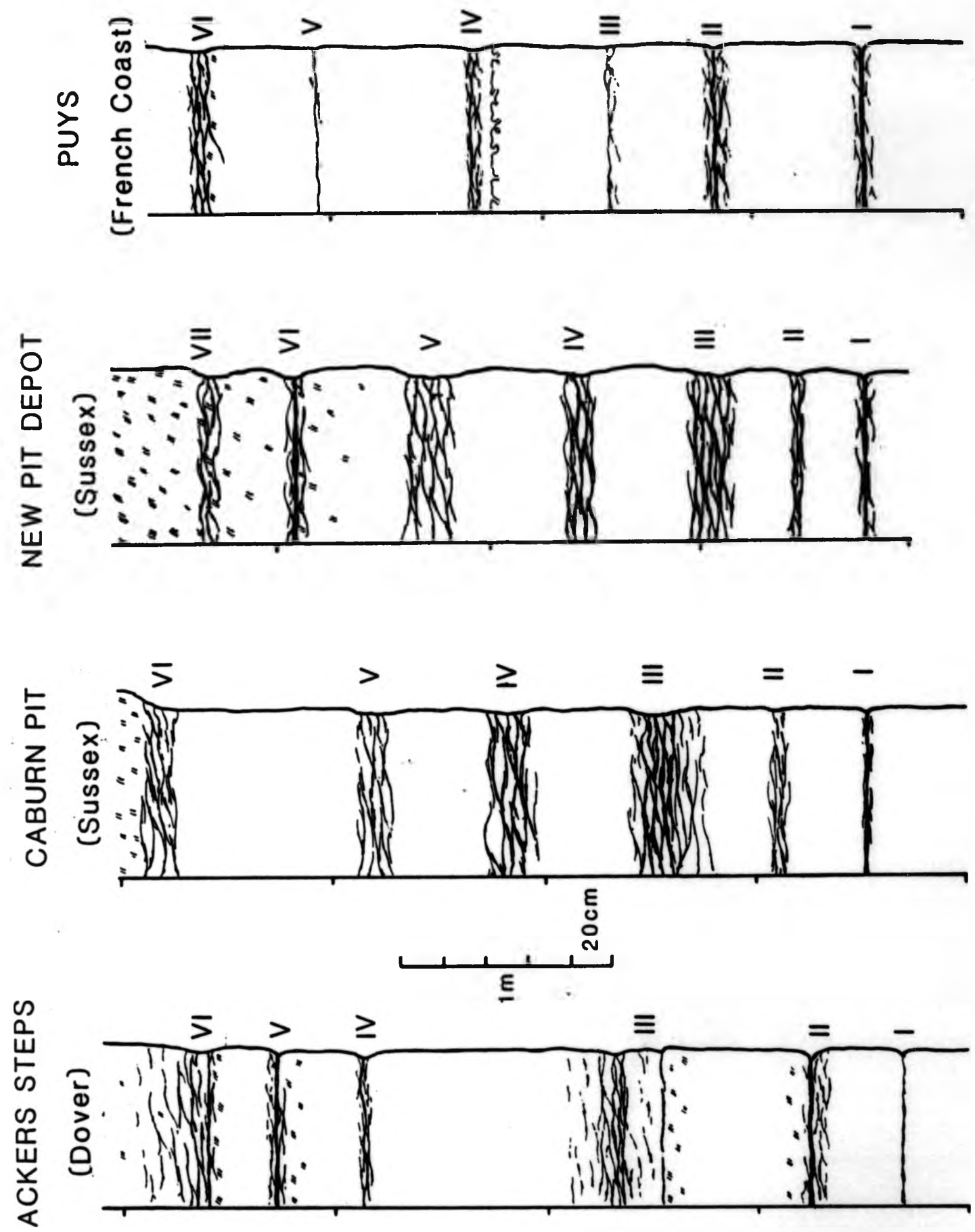


Figure A2.5: Southerham Marls

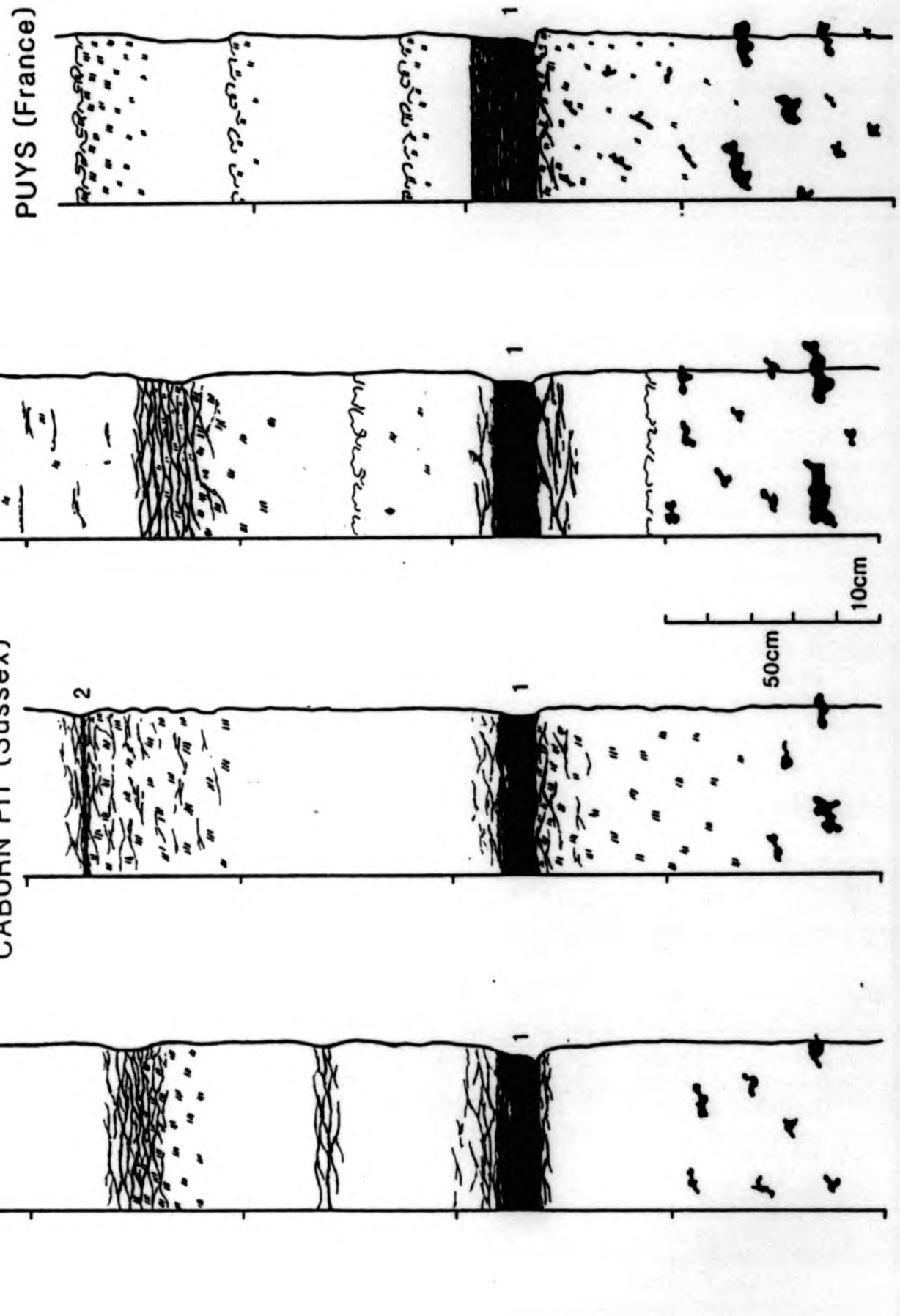


Figure A2.6: Caburn Marl

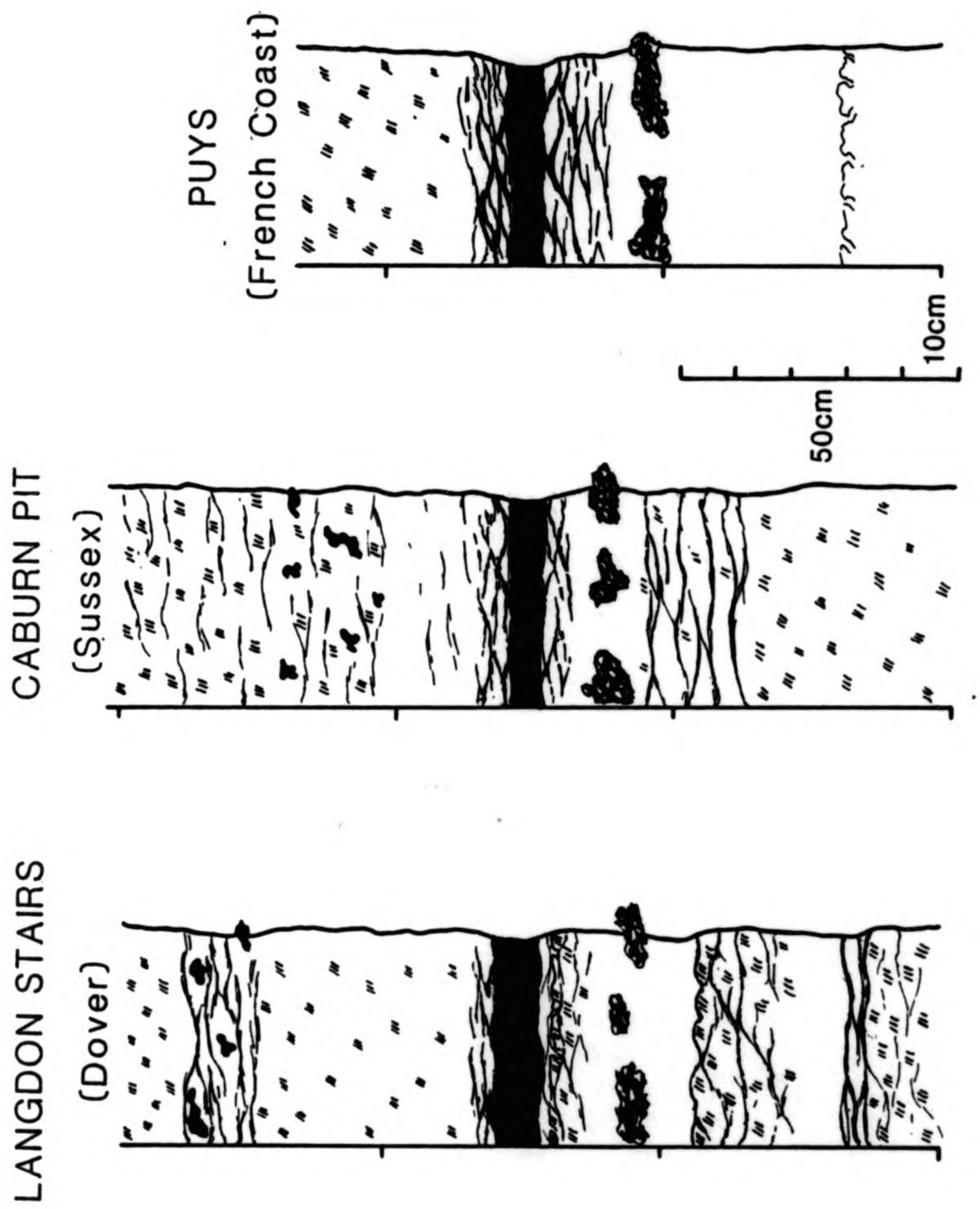


Figure A2.7: Bridgewick Marls

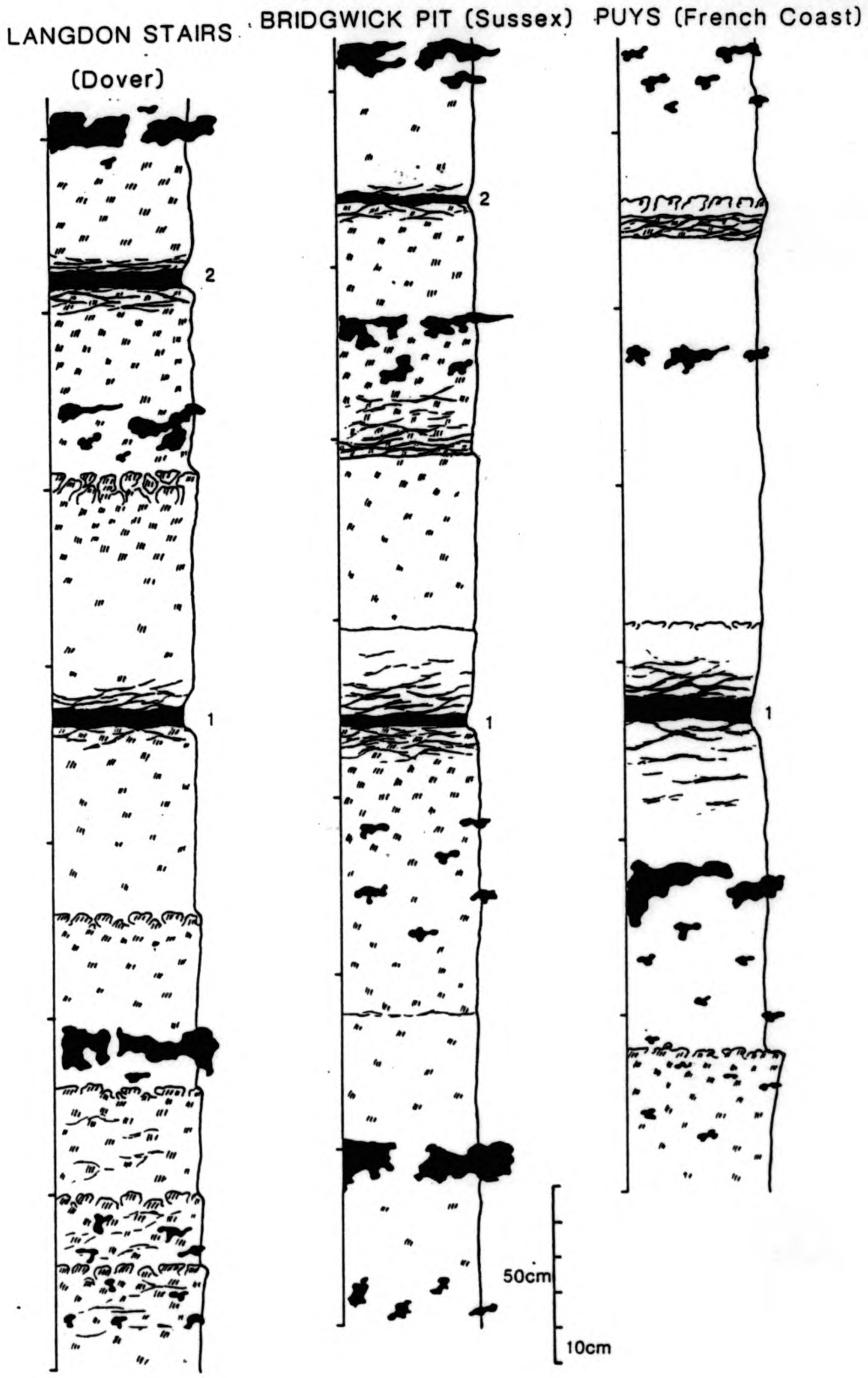
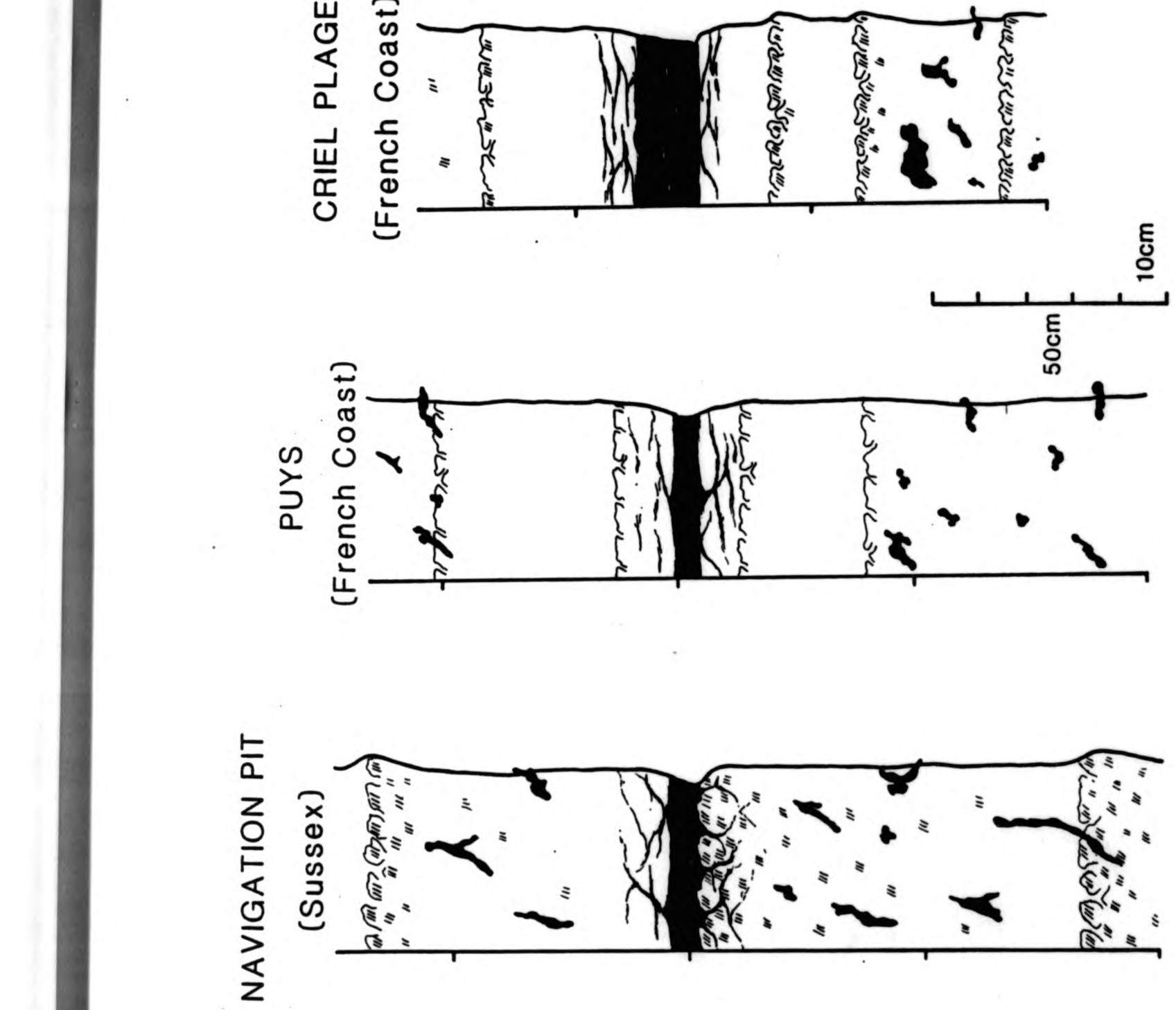


Figure A2.8: Lewes Marl



PLATES TO ACCOMPANY TEXT

Plate 1

a) Southerham Marl 1 (labelled S1) - a good example of a thick type A marl. Note below it the presence of thin finger flints (examples labelled ff) which are often associated with this marl (Eletot, French Coast).

b) New Pit Marl 2 (a type B marl) displaying beneath it a well developed intraclastic unit (labelled I); Akers Steps, Dover.

PLATE 1

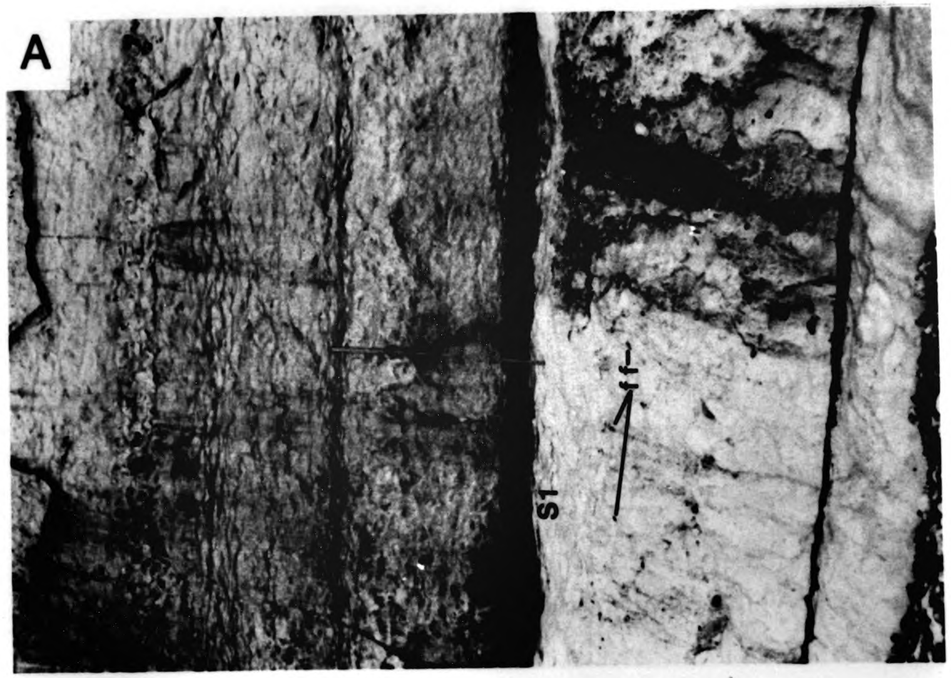


Plate 2

a) New Pit Marl 1, a good example of a type C flaser marl; between Puys and Belleville on the French Coast.

b) Malling Street Marl (labelled M) showing the association between the nodules which separate the flasers and the nodular surface above (labelled S); Akers Steps, Dover.

PLATE 2

A

B

Plate 3

a) New Pit Marl 1 showing ?*Thalassinoides* or ?*Planolites* (examples labelled R) reworking the marly chalk and occasionally the white chalk; between Puys and Belleville on the French Coast.

b) Bridgewick Marls 1 and 2 (labelled) showing the transformation of Marl 2 from a type B (labelled B) to a type D marl (labelled D), seen between Langdon Stairs and St Margarets Bay, Dover; distance between the marls is approximately 1.20 m.

PLATE 3

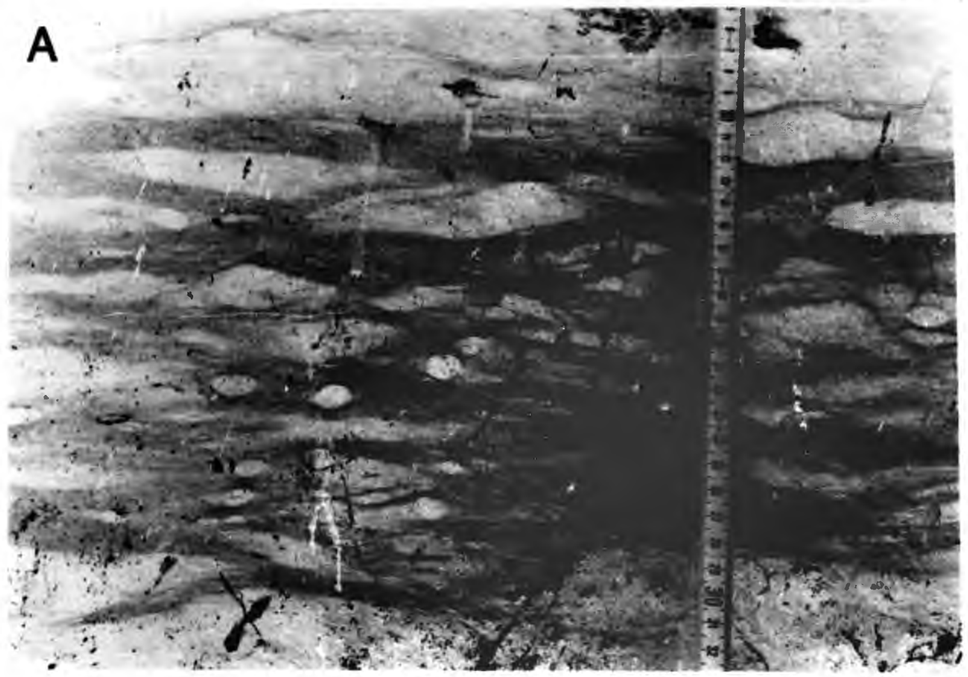


Plate 4

a) A well preserved burrow below New Pit Marl 2, note the presence of white intraclasts (labelled I) and reworking burrows (labelled R) infilled with white chalk; Beachy Head, Sussex.

b) Numerous white burrows (examples labelled B)close to the top of the Fecamp Marl, probably a combination of *Thalassinoides* and *Planolites* (Fecamp, French Coast).

PLATE 4

A

B

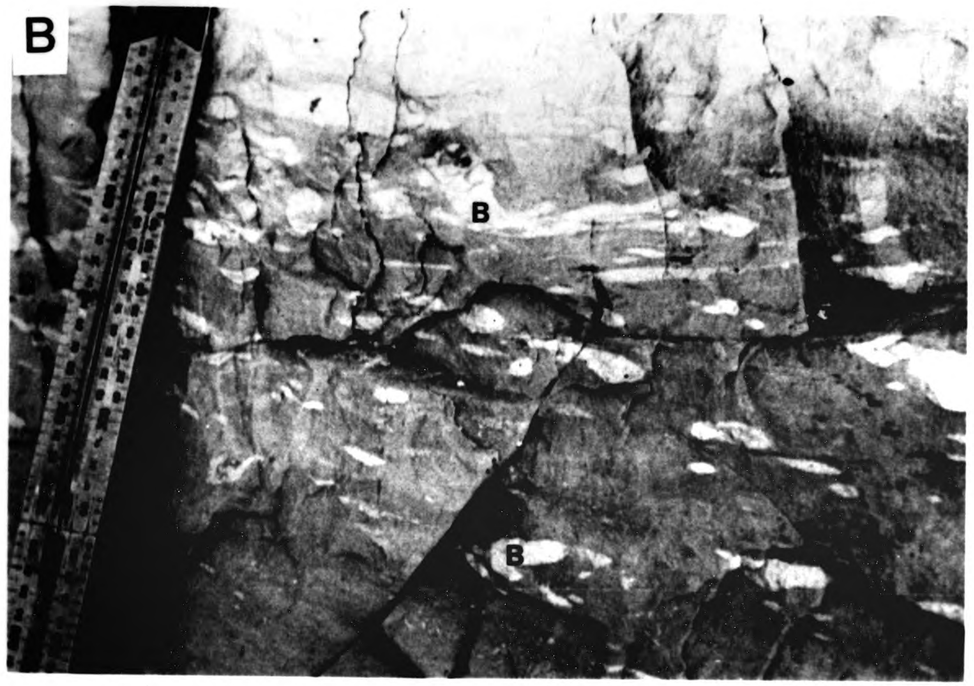


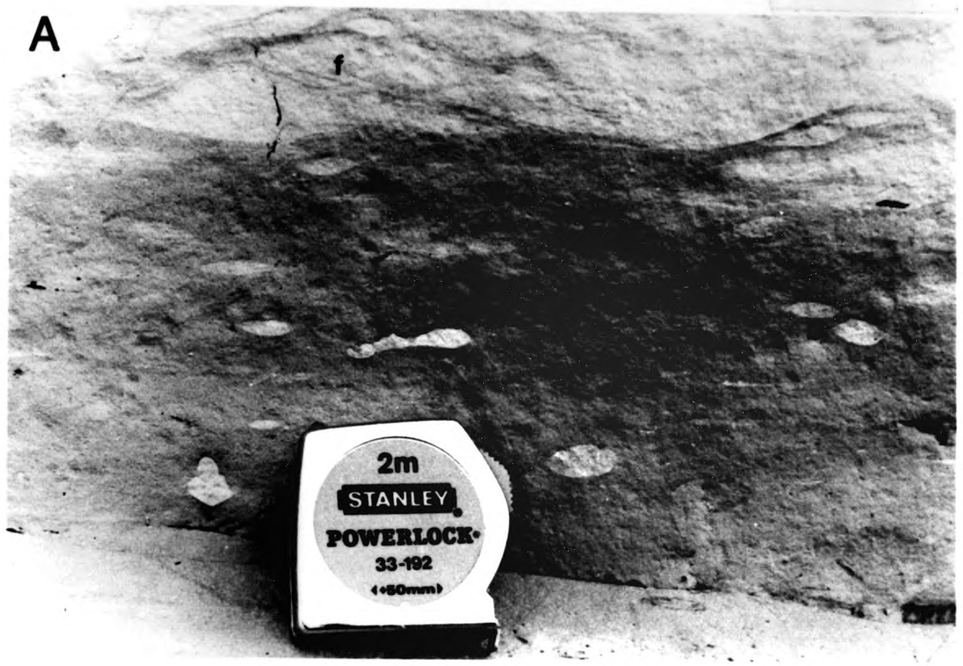
Plate 5

a) Isolated burrows ?*Thalassinoides* or?*Planolites* (labelled b) seen in New Pit Marl 2. Note also the flasers developed above the marl seam (labelled f); between Puys and Belleville, French Coast.

b) Plan view of burrows close to the base of New Pit Marl 2. Note the core of marly chalk in the large burrow slightly below the centre of the photograph (labelled c); between Puys and Belleville, French Coast.

PLATE 5

A



B

Plate 6

a) Well defined omission surface (labelled OS) showing the omission suite of *Thalassinoides* burrows (labelled OB) to be partially infilled with soft white chalk intraclasts (labelled I). The burrows have been partially deformed by subsequent compaction. Nodules in the chalk above the surface are associated with an overlying, partially cemented surface. Note also flint development occurring preferentially in burrows and above the surface; Upper Turonian, Puys, French Coast.

b) Weakly nodular omission surface (labelled OS) displaying post-omission *Zoophycos* burrows (labelled Z) above the surface and reworking omission suite burrows, seen between Langdon Stairs and St Margarets Bay, Dover. Note that whilst some of the burrows have been slightly deformed around nodules at the surface, the majority appear unaffected, implying that the producing organisms were relatively deep burrowing. Flasers are absent above the surface, possibly because the amount of clay within the sediment is too low.

PLATE 6

Plate 7

a) A wave-washed, well developed nodular omission / erosion surface (labelled S) between Langdon Stairs and St Margarets Bay, Dover. Early cemented chalk extends downwards over 60 cm and is capped by a scattering of weakly nodular chalk intraclasts. Note the development of flints in the more uniform chalk above.

b) Oblique plan view of the mineralized Tillieul Hardground (labelled HG) at Senneville on the French coast. Patches of lighter chalk on the hardground either represent later infilling of depressions in the surface, or the entrance to omission suite *Thalassinoides* burrows which have subsequently been infilled.

PLATE 7

Plate 8

a) Plan view of flint replacing a branching *Thalassinoides* burrow system (between Langdon Stairs and St Margarets Bay, Dover).

b) Flint developed in softer chalk, and surrounding a white chalk nodule (Langdon Stairs, Dover).

PLATE 8

A

B

Plate 9

Marly chalk and nodules at the base of Bridgewick Marl 2 (Dover) showing evidence of dissolution (labelled d) due to pressure solution. Note that the usually softer marly chalk above and below the nodules is harder than the nodules, indicating some of the dissolved calcite was re-precipitated almost immediately.

PLATE 9

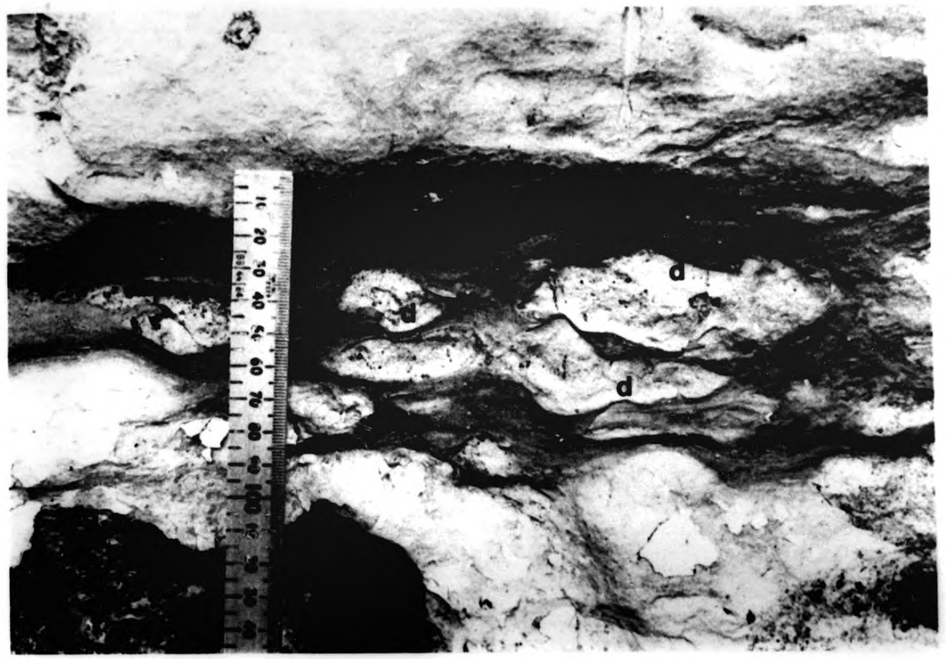
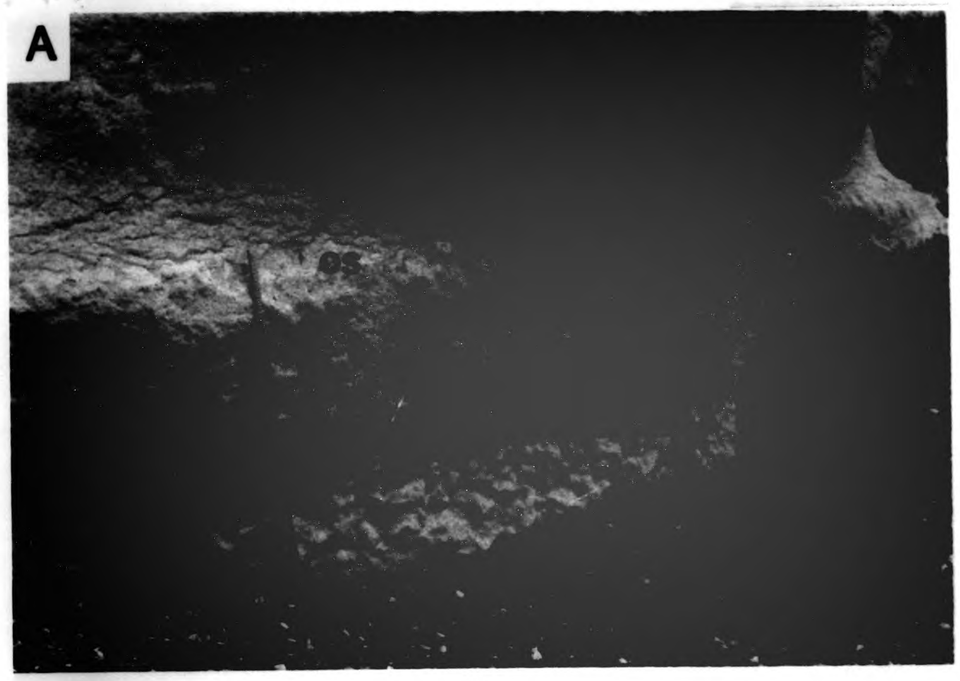


Plate 10

a) Irregular, sub-horizontal flasers (labelled F) developed above a series of nodular omission surfaces (labelled OS) between Langdon Stairs and St Margarets Bay, Dover.

b) Thin sub-horizontal flasers resting on one well defined and one poorly defined omission surface at Beachy Head, Sussex. Variations in the amount of flasering are probably related to slight differences in the amount of clay in the sediment.

PLATE 10



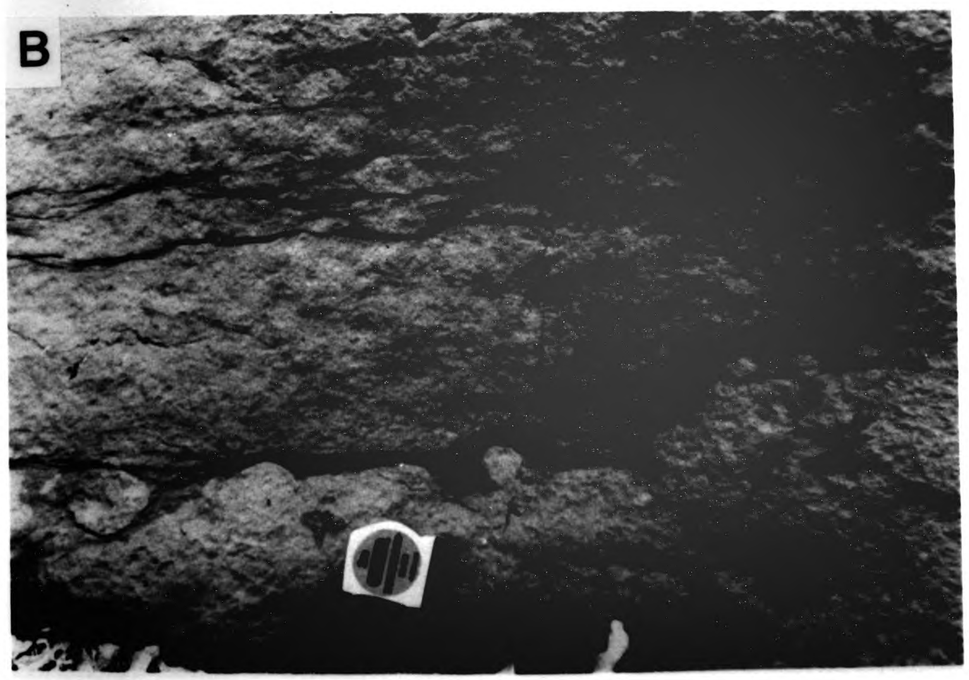


Plate 11

Thick flasers (labelled F) developed below a slightly nodular omission surface (labelled OS) between Langdon Stairs and St Margarets Bay, Dover.

PLATE 11

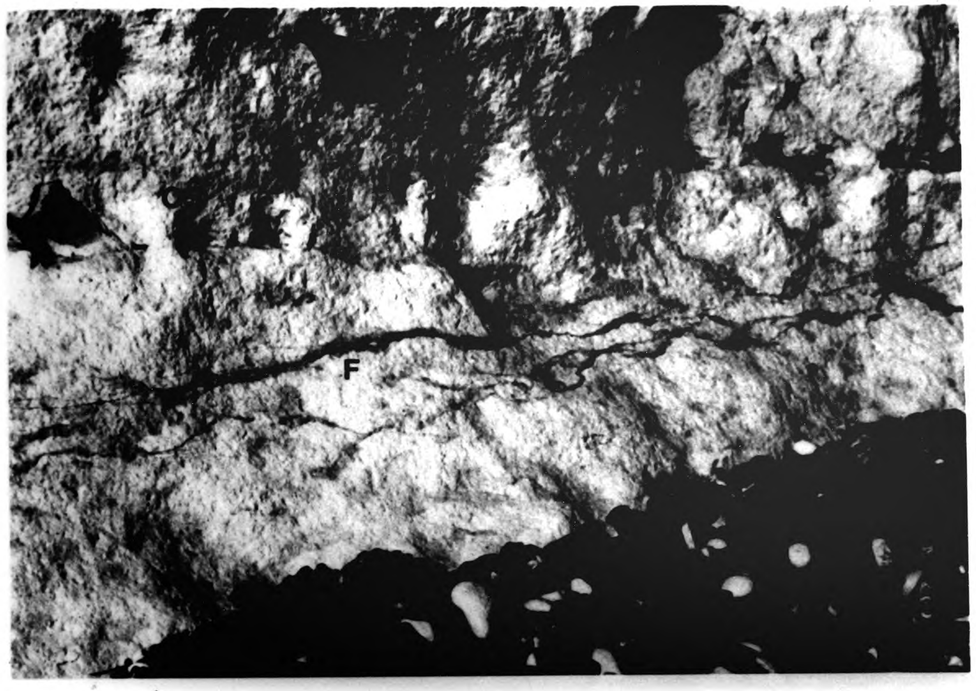


Plate 12

a) Sectioned core showing flaser development in light grey burrow chalk (labelled B). Note, where nodules are present, the tendency for flaser to be developed close to the firmer chalk. Turonian, Faircross Borehole (core courtesy of R.N. Mortimore).

b) Sectioned core showing the displacement of flasers by flints (labelled F), indicating that the flints were introduced prior to the development of the flasers; Turonian, Faircross Borehole (core courtesy of R.N. Mortimore).

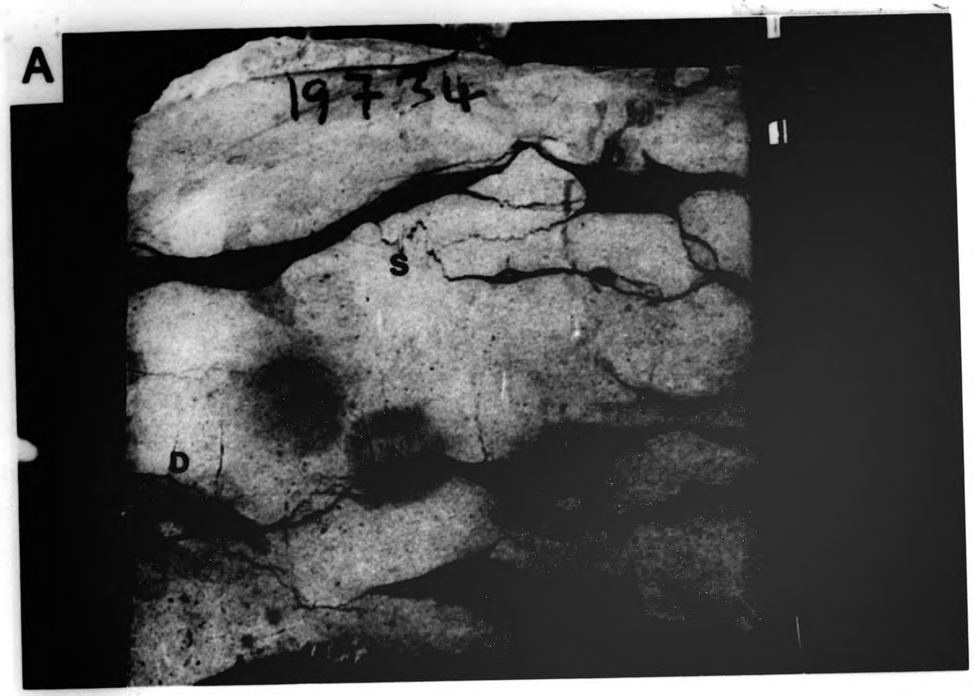
PLATE 12

Plate 13

a) Sectioned core showing flasers expanding and becoming more diffuse (labelled D) in areas of softer burrow chalk. Note also the development of stylolites where localised compaction severe (labelled S); Turonian, Faircross Borehole (core courtesy of R.N. Mortimore).

b) Wave-washed surface showing flasers developed in a large burrow. Note that the flasers are concentrated against the firmer white chalk at the base of the burrow; Beachy Head, Sussex.

PLATE 13



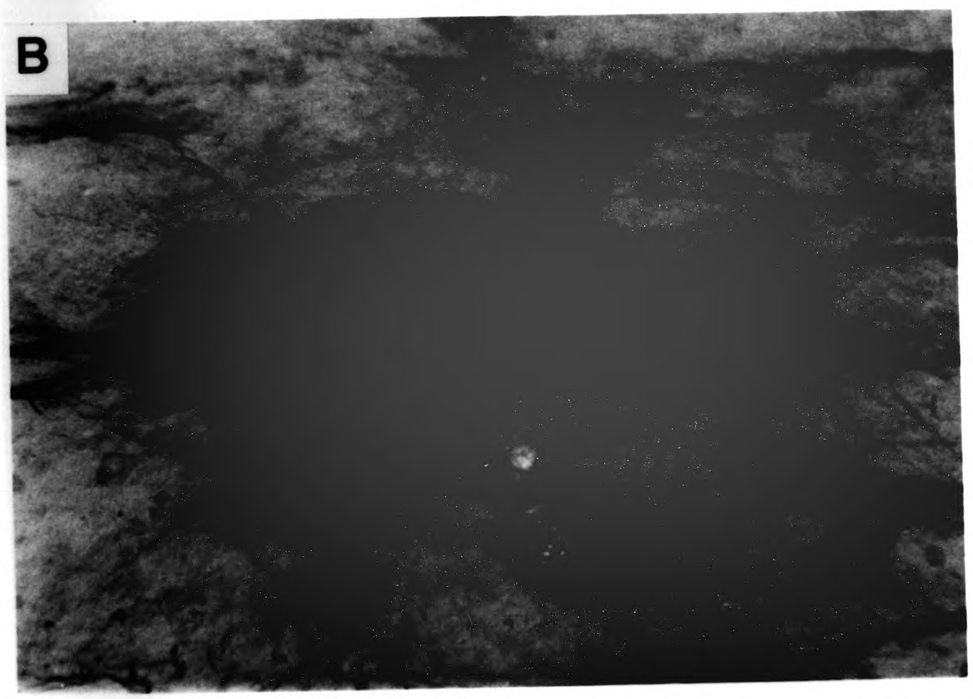


Plate 14

Scanning electron microscope photographs of selected grains from Southerham Marl 1, Eletot.

A) - C) Quartz grains showing a range of surface textures:

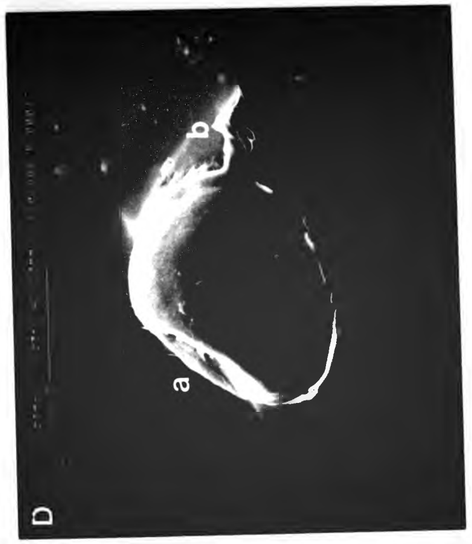
A) Sub-angular grain with concoidal fractures, which has presumably undergone a limited amount of transportation.

B) Well-rounded grain with a very smooth surface with only occasional indentations in it, indicative of a grain which has undergone an extended period of aqueous transportation and erosion.

C) Well-rounded grain with an uneven, well pitted, frosted surface, indicative of aeolian erosion and transportation.

D) Organic spherule with and indentation at one end (a) and a short tail at the other (b).

PLATE 14



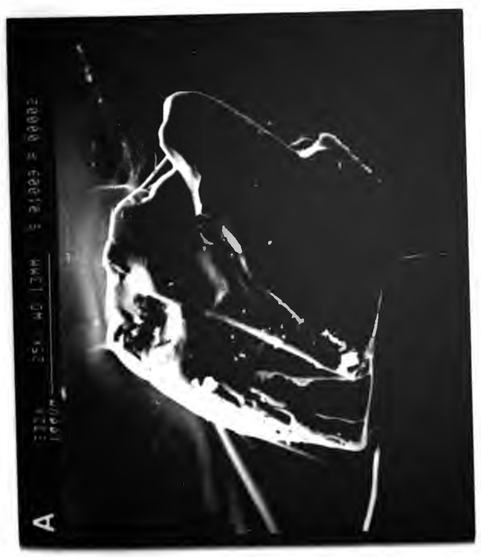


Plate 15

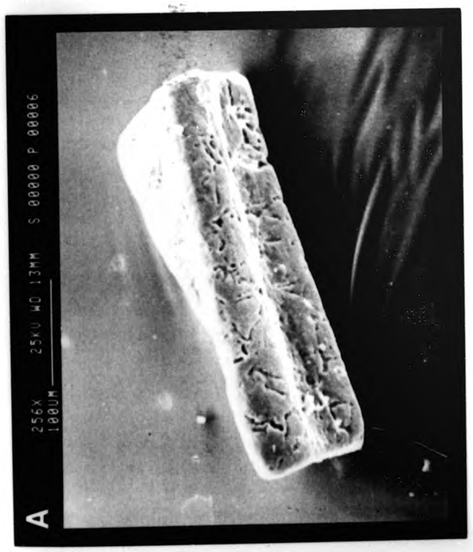
Scanning electron microscope photographs of selected grains from Southerham Marl 1, Eletot (cont).

A) - B) Carbonate-apatite grains believed to be derived from vertebrate skeletons. The the indented networks visible on the surface are likely to be derived from the activities of boring organisms whilst the grains were exposed on the sea-floor.

C) Well formed authigenic sphalerite crystal.

D) Authigenic crystals of pyrite which alter to limonite during sub-aerial weathering.

PLATE 15



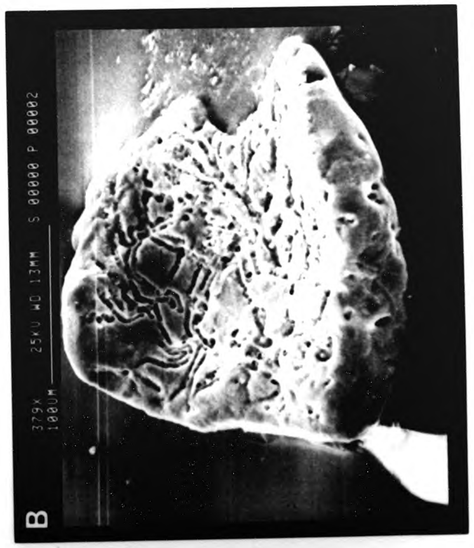


Plate 16

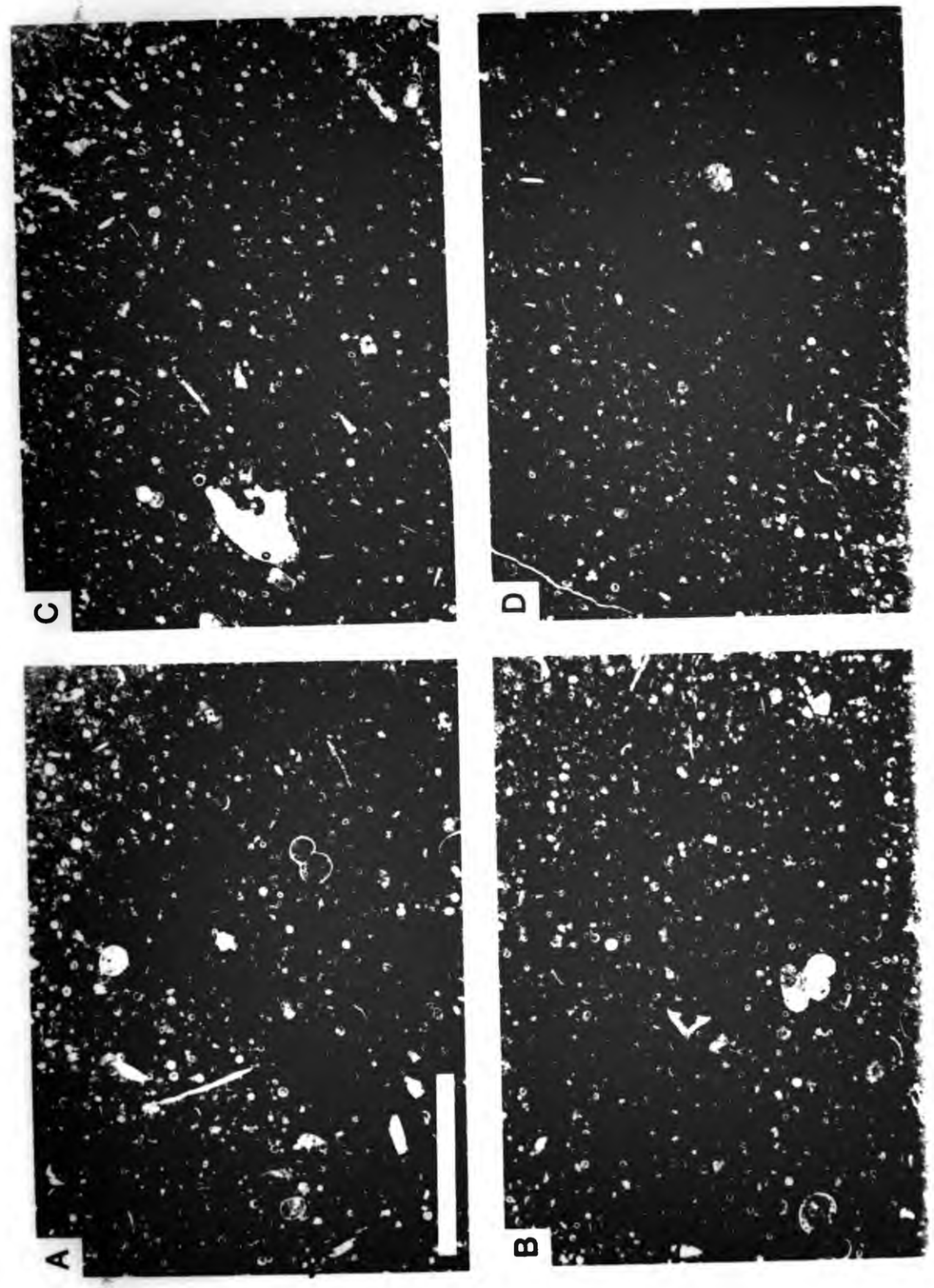
A series of photomicrographs taken from samples above, below and within New Pit Marl 1 from Beachy Head. They illustrate that the formation of the marl had little effect on the composition of the coarse carbonate grains, other than to reduce their total number through dilution with clay. The scale marker in A is 1 mm in width and is applicable to all subsequent photomicrographs.

A and B Calcisphere-rich white chalk with a wackestone texture from above New Pit Marl 1.

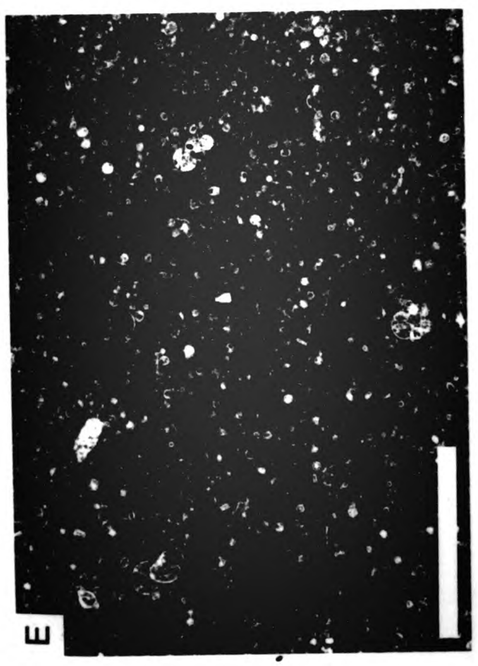
C and D Examples of the mudstone texture displayed by New Pit Marl 1. The black, irregular sub-horizontal line extending part of the way across (D) is probably an indication that some post-burial dissolution of carbonate has taken place. The light, criss-crossing lines on both photgraphs are relicts of the thin-section making process.

E and F Calcisphere-rich white chalk with a mudstone-wackestone texture from below New Pit Marl 1. The scale marker in E is 1 mm in width and is applicable to both photomicrographs.

PLATE 16



F



E

Plate 17

Photomicrographs of samples taken within, above and below New Pit Marl 2 from Beachy Head. The white chalks from above and below have a similar mudstone-wackestone texture whilst the marl has a coarser, packstone texture reflecting the incorporation of winnowed material from the underlying erosion surface. The scale marker in A is 1 mm in width and is applicable to all subsequent photomicrographs.

A and B — Calcisphere rich white chalk with a mudstone-wackestone texture from above New Pit Marl 2. There is little breakage or alignment of grains, and the number of large macrofauna derived grains is low.

C and D — White chalk from below New Pit Marl 2 and its underlying erosion surface, displaying a similar texture to the white chalk from above the marl.

E — Example of the packstone texture displayed by New Pit Marl 2, note the sub-parallel alignment of many of the large grains and the increase in number of large, macrofauna derived fragments. The scale marker is 1 mm in width and is applicable to all subsequent photomicrographs.

F — Thin, anastomising clay networks found within New Pit Marl 2, good evidence that dissolution of carbonate through pressure solution has taken place within the marl.

G — A well-worn, large, macrofauna-derived fragment which is aligned parallel to the principal compression direction. During burial it partially prevented compaction of chalks on either side of it, as illustrated by the lighter coloured areas (a and b), but its resistance to compaction resulted in dissolution of carbonate through pressure solution being concentrated at either end (c and d). N.B. the orientation of the photomicrograph is such that the principle compression direction is horizontal.

H — Pseudo-volcanic shards composed of carbonate-apatite. The fragments are more likely to be derived from vertebrates living within the Anglo-Paris Basin.

PLATE 17

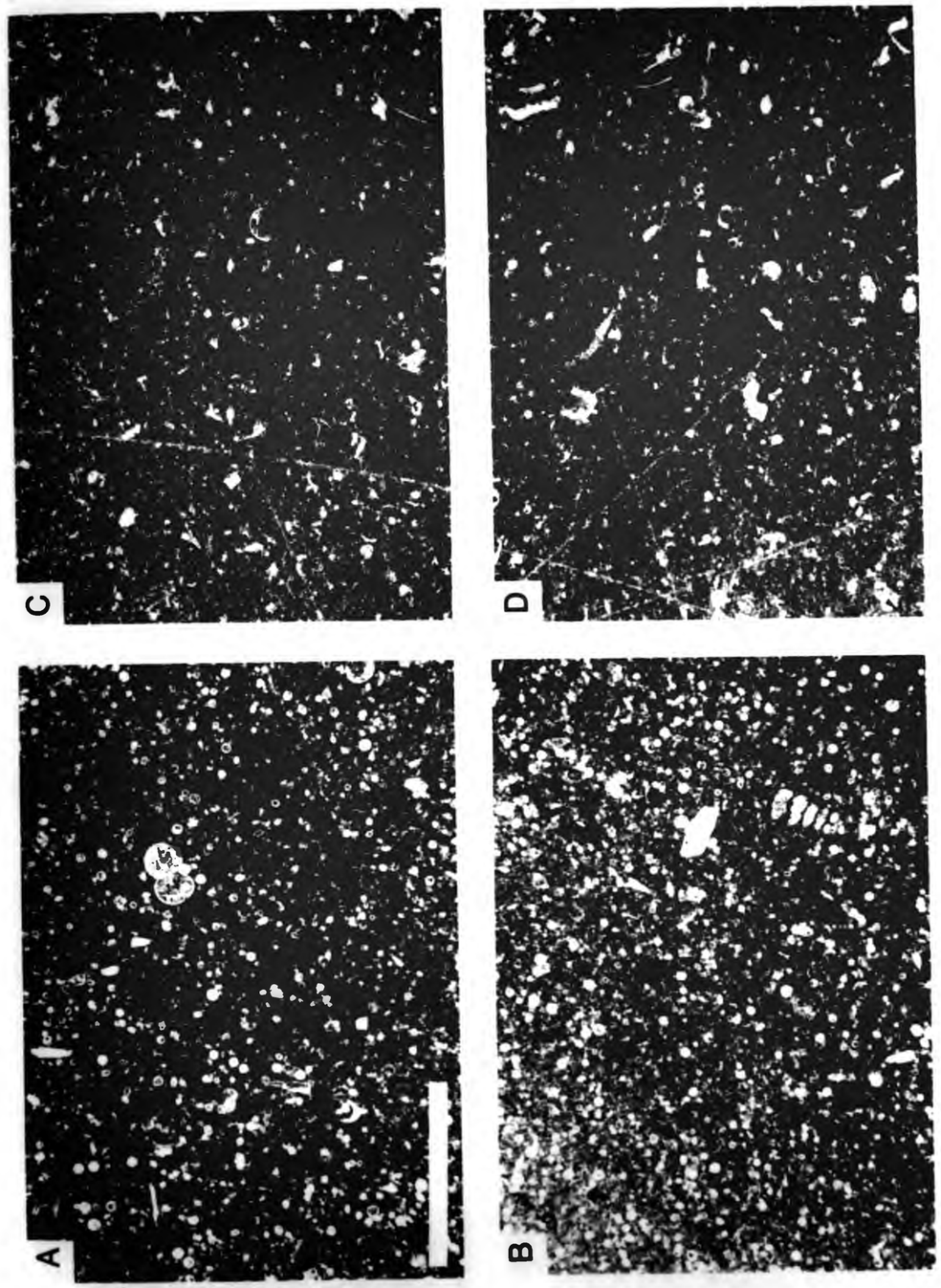


PLATE 17 cont.

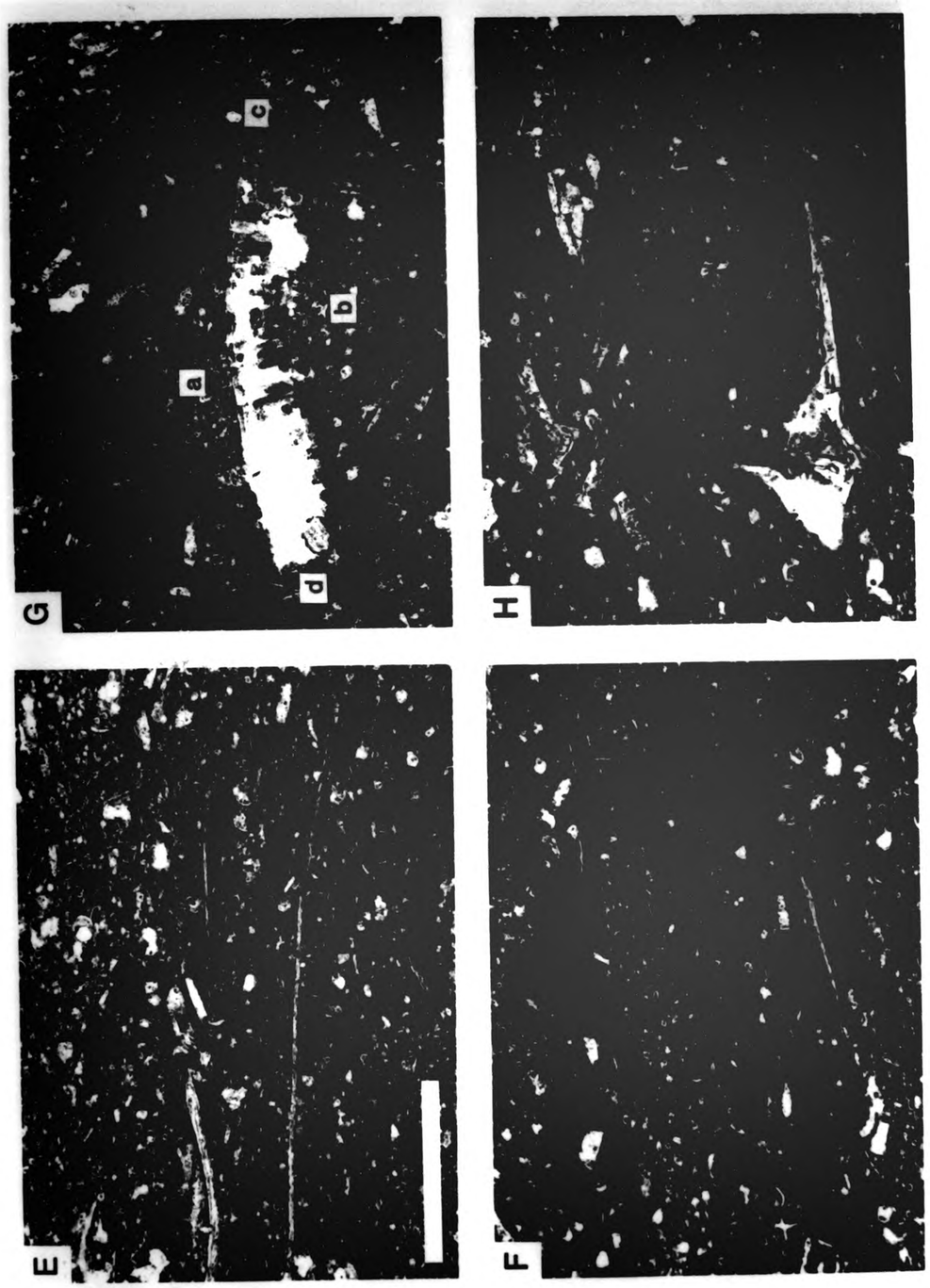


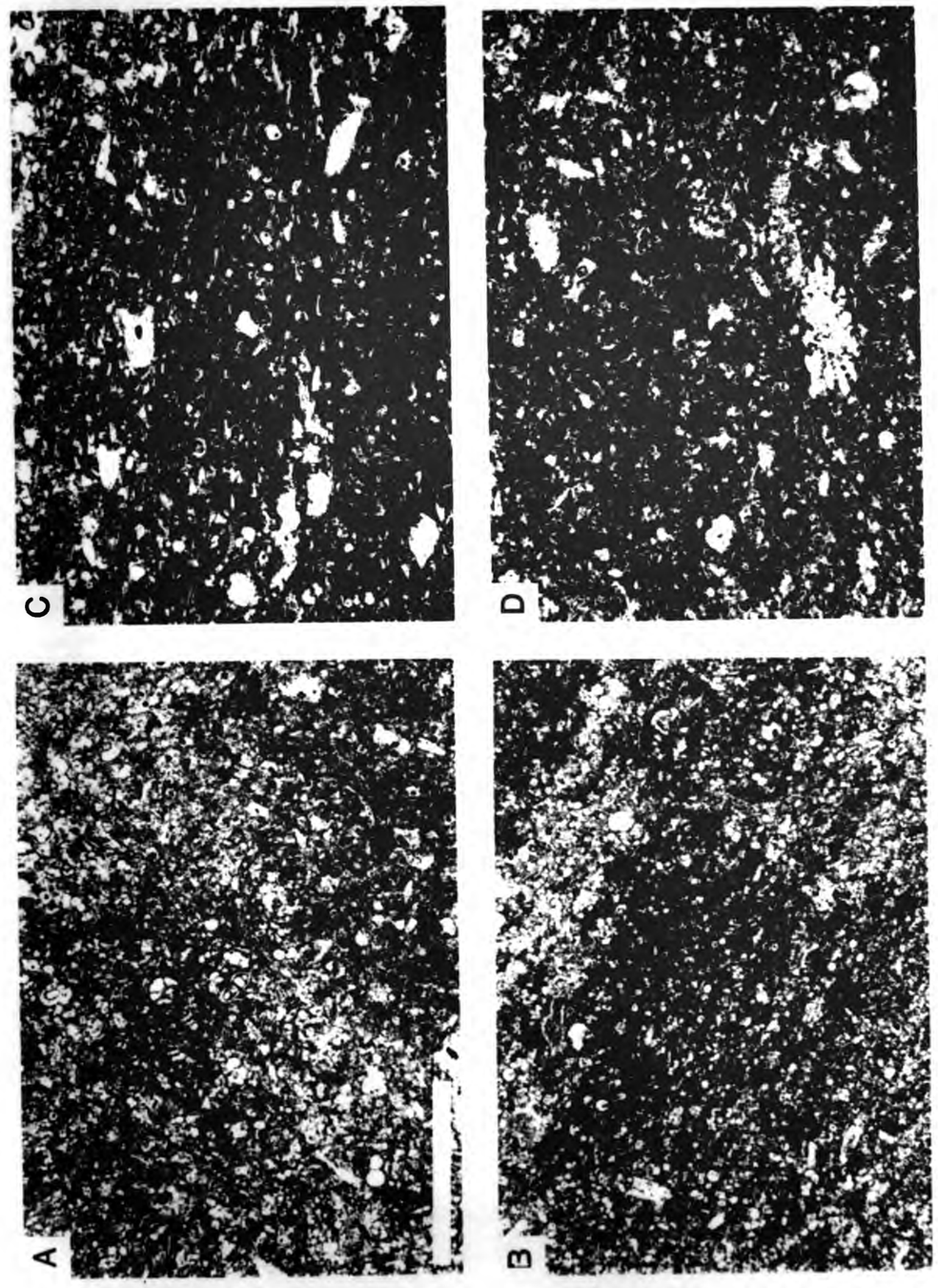
Plate 18

A series of photomicrographs taken from samples adjacent to- and within Bridgewick Marl 2 from Dover, demonstrating that the coarse nature of the chalks adjacent to the marl is continued within the seam. The scale marker in A is 1 mm in width and is applicable to all subsequent photomicrographs.

A and B White chalk adjacent to Bridgewick Marl 2 displaying a wackestone-packstone texture. The coarse particle consist of a randomly orientated mixture of calcispheres, whole foraminifera and fragments of macrofossils. The dark line passing diagonally across B is an artifact of the thin section making process.

C and D Marly chalk from Bridgewick marl 2 displaying a wackestone-packstone texture. Although the clay slightly obscures many of the coarse clacitic particles, their number and composition is broadly similar to that seen in adjacent white chalks. Large fragments derived from the macrofauna are more common than in the white chalk, an indication that the marl may overlie an erosion surface. Coarse particles in (C) show a crude alignment at right angles to the principle compression direction and there are fewer whole forams, possibly due to the effects of compaction.

PLATE 18



APPENDIX 1

LOCALITIES AND LOCALITY LOGS

Introduction

Marl bands described in this report have been examined in four areas: Kent, Sussex, the Chilterns and the French coast. Where possible, wave-washed coastal sections have been used in preference to inland pits due to the fresher nature of the marls when wave-washed. Detailed stratigraphic logs have been measured at most localities. Below are listed the grid references for all localities mentioned in the text, and the relevant stratigraphic log.

For details of locations in the Northern Province the reader is referred to Wood and Smith, 1978.

Criel Plage#	$\overline{1}.\overline{14}.$,55,59	*M & P, fig. 13*	
Eletot	$\overline{2}.\overline{12}.$,55,32	*M & P, fig. 14*	
Etretat	$\overline{2}.\overline{37}.$,55,23	*Q*	
Puys	$\overline{1}.\overline{36}.$,55,48	fig. A1.15•	A23
Senneville#	$\overline{2}.\overline{14}.$,55,31	*M & P, fig. 14*	

Please Note:

1) A • signifies that the section extends further than the log presented in this thesis.

2) A # signifies that a log is not included within this work, either because only one marl was collected from the section, or that the section is only mentioned in passing. The reader is directed to previously published logs as follows:

M = Mortimore, 1986a.

M & P = Mortimore and Pomerol, 1987.

Q = Quine, 1988.

Figure A1.1

KEY FOR ALL SECTIONS

White chalk

Flint band

Tabular flint

Omission surface

Nodular omission surface

Hardground

Nodular chalk

Intraclastic chalk

Isolated flasers

Flaser marl

Marl seam

Malling Street Marl

Figure A1.2

AKERS STEPS

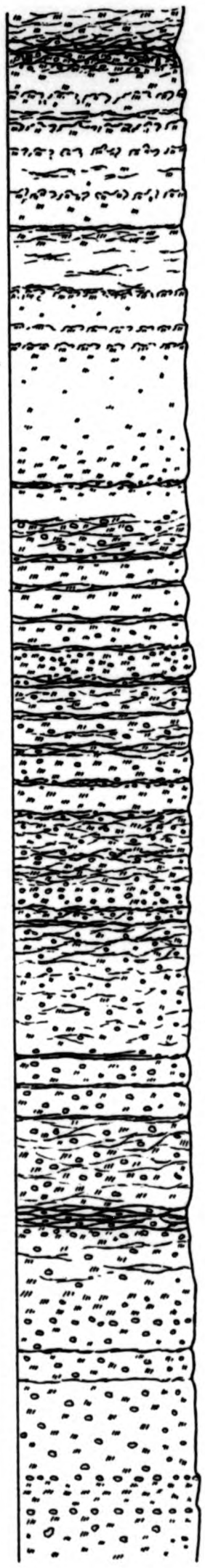


Figure A1.2 cont.

AKERS STEPS

A FAULT OCCURS APPROXIMATELY 2.5 m BELOW NEW PIT MARL 1 ON AKERS STEPS. IT IS DIFFICULT TO MEASURE THE DISPLACEMENT ACROSS THE FAULT DUE TO INACCESSIBILITY AND A LACK OF SUITABLE MARKER HORIZONS. EXAMINATION OF THE SECTION MEASURED ON LYDDEN SPOUT PATH INDICATES THAT THE FAULT MAY HAVE SHORTENED THE SECTION ON AKERS STEPS BY 1-2 m, ALTHOUGH THIS DOES NOT TAKE INTO ACCOUNT THE POSSIBILITY OF CONDENSATION OCCURRING BETWEEN THE TWO LOCALITIES.

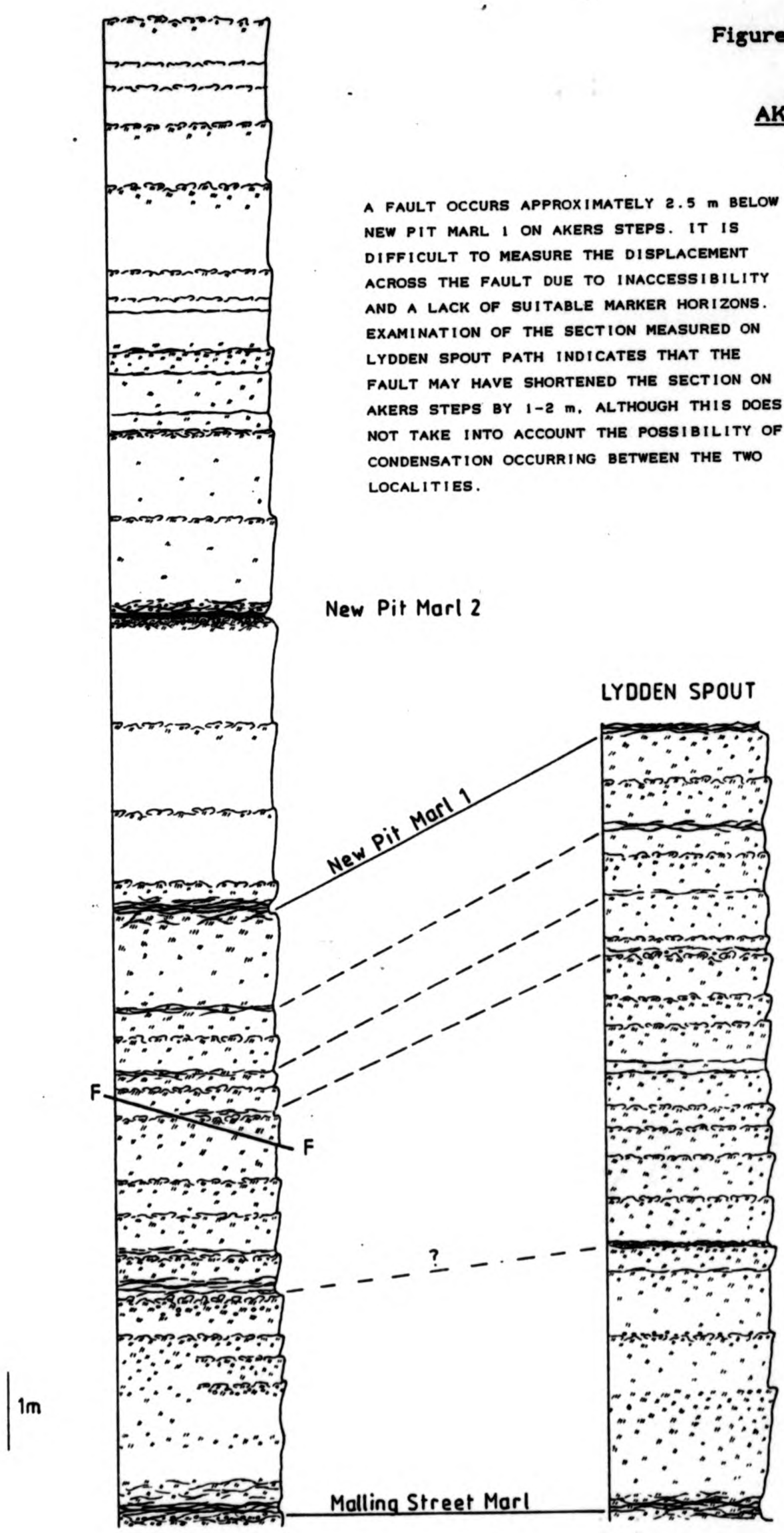


Figure A1.2 cont.

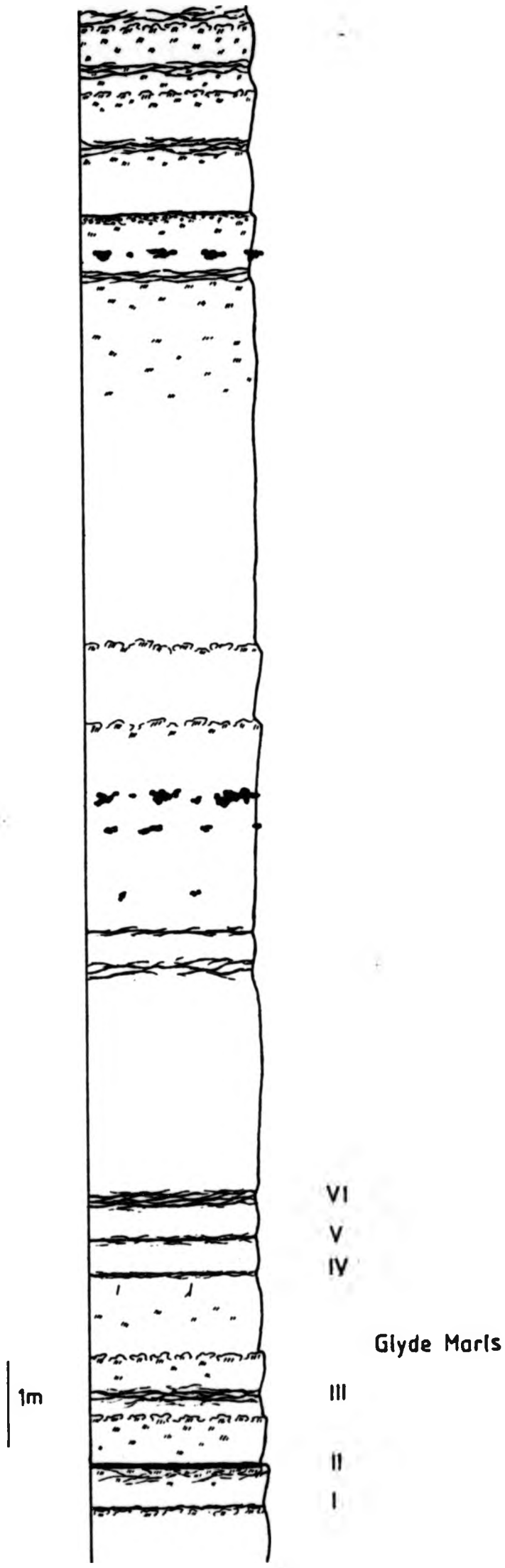


Figure A1.2 cont.

AKERS STEPS

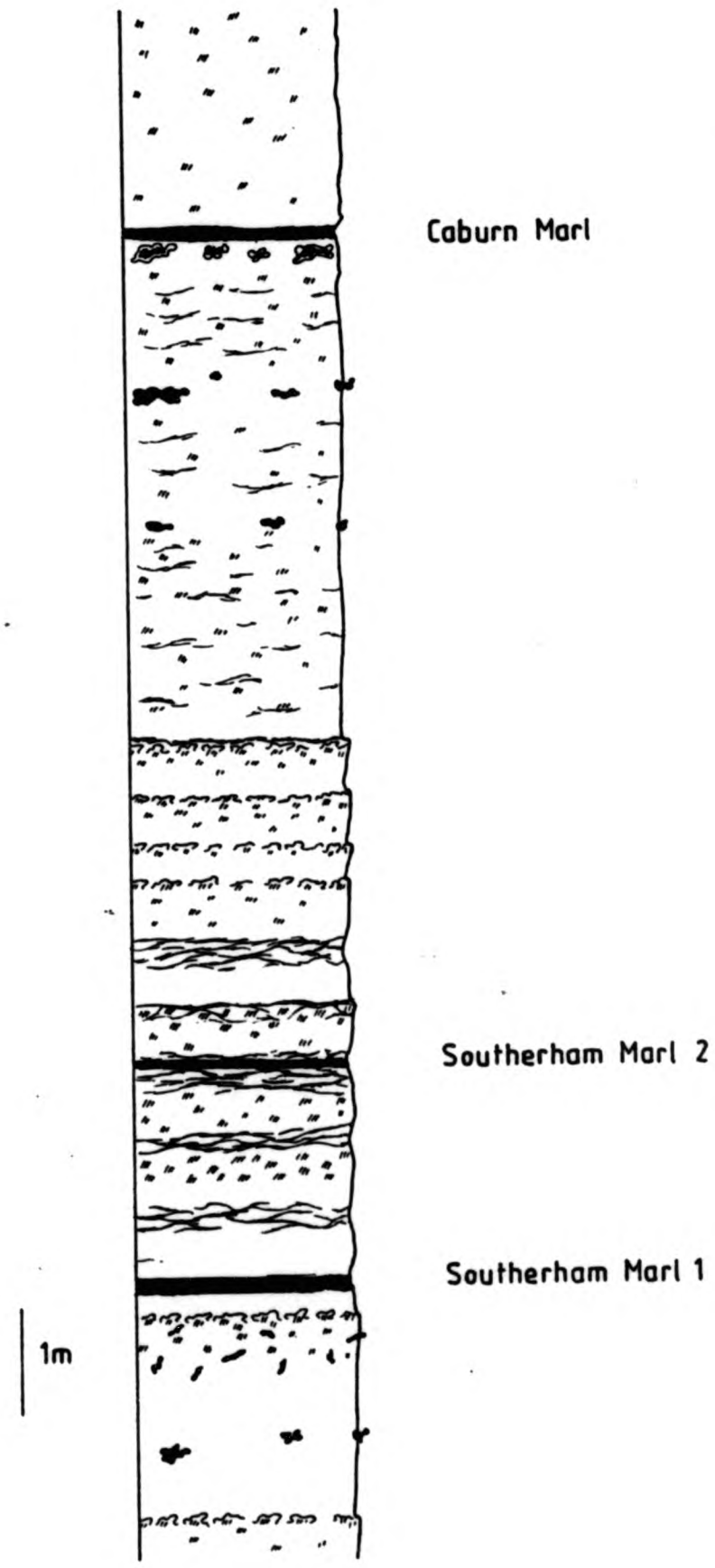
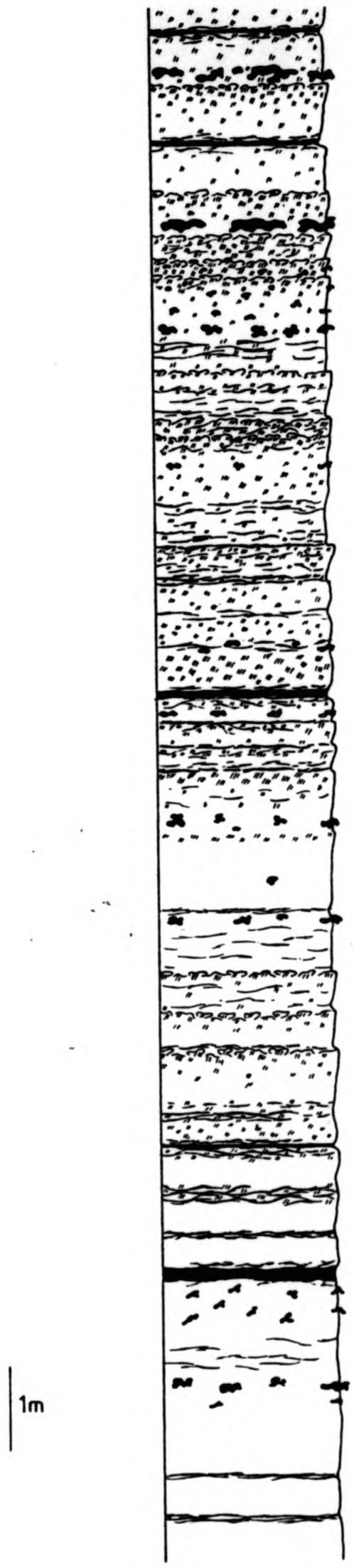


Figure A1.3



LANGDON STAIRS

Figure A1.3 cont.

LANGDON STAIRS

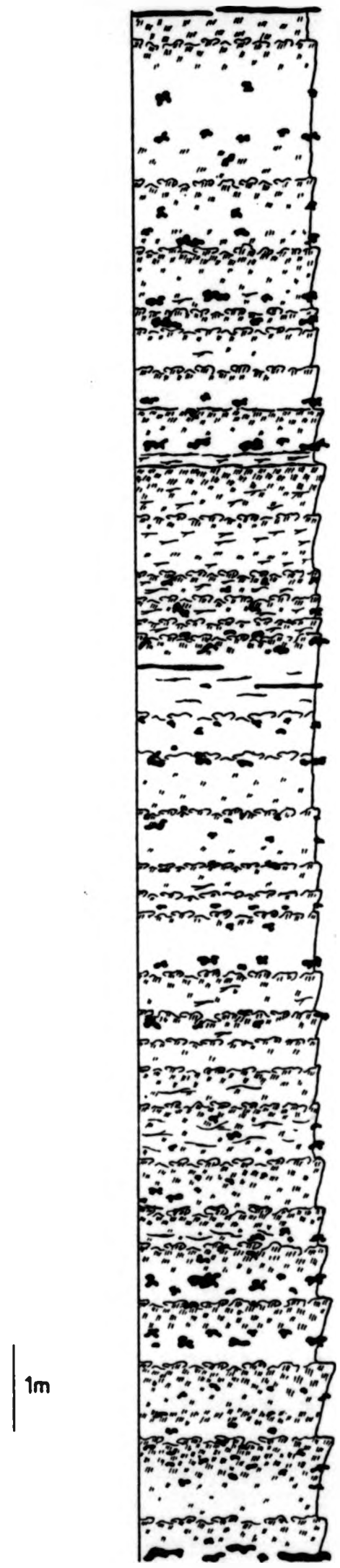


Figure A1.4

BEACHY HEAD

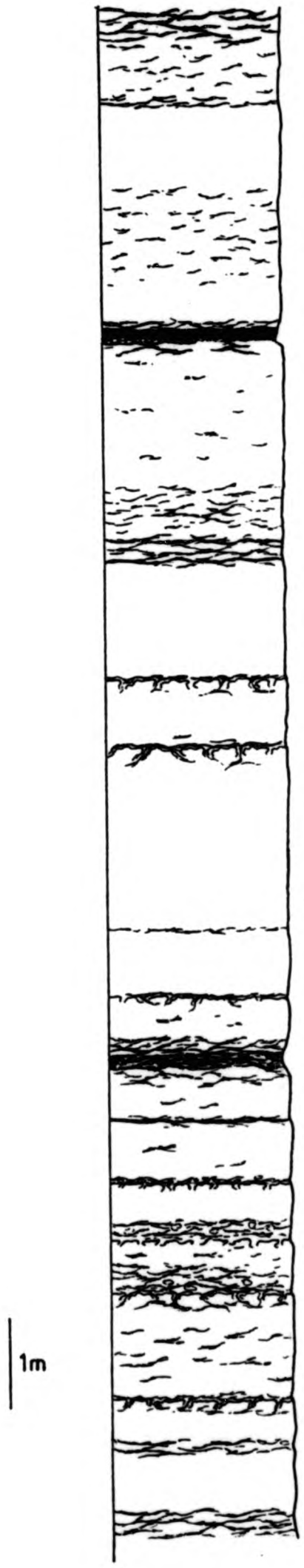


Figure A1.5

BRIDGWICK PIT

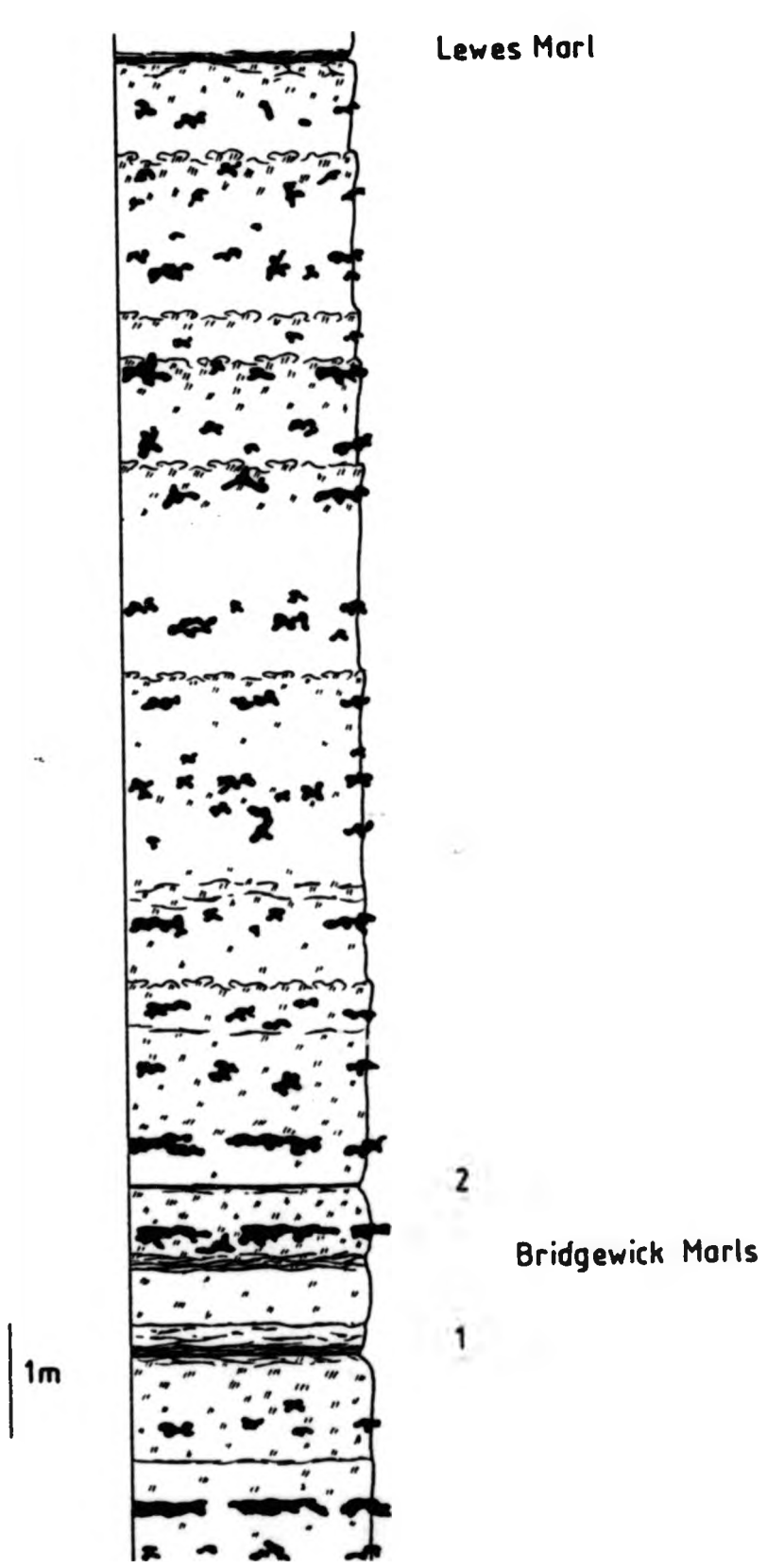


Figure A1.6

CABURN PIT

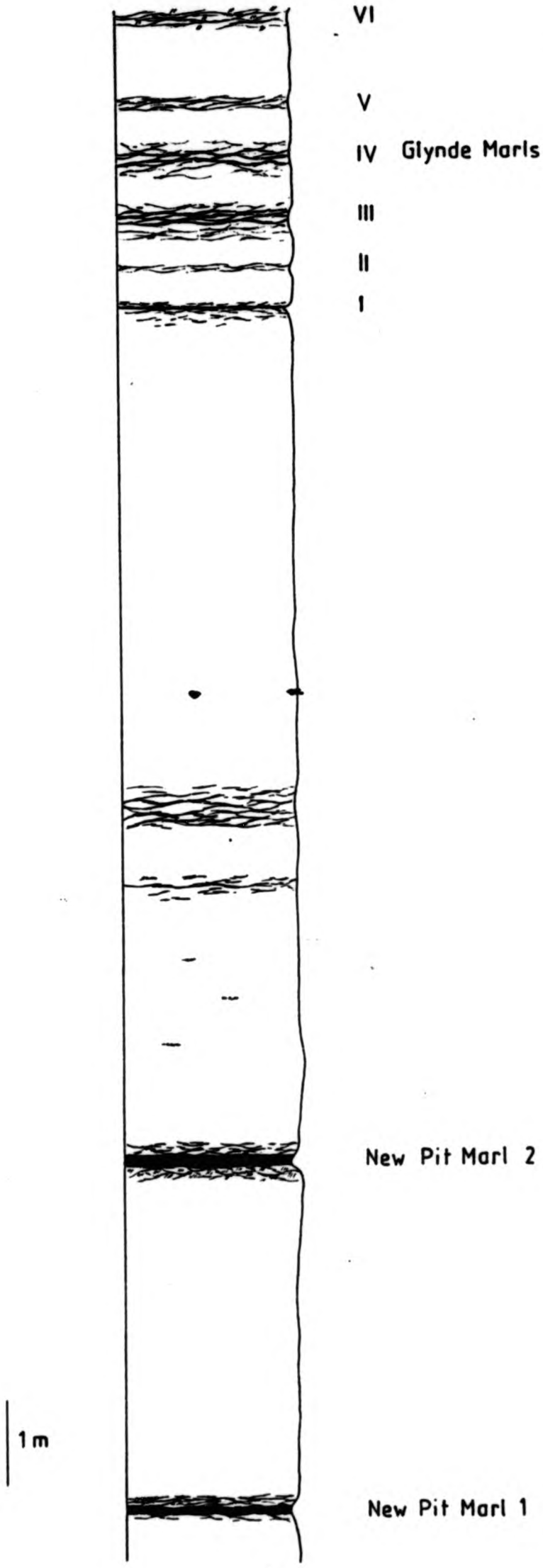


Figure A1.6 cont.

CABURN PIT

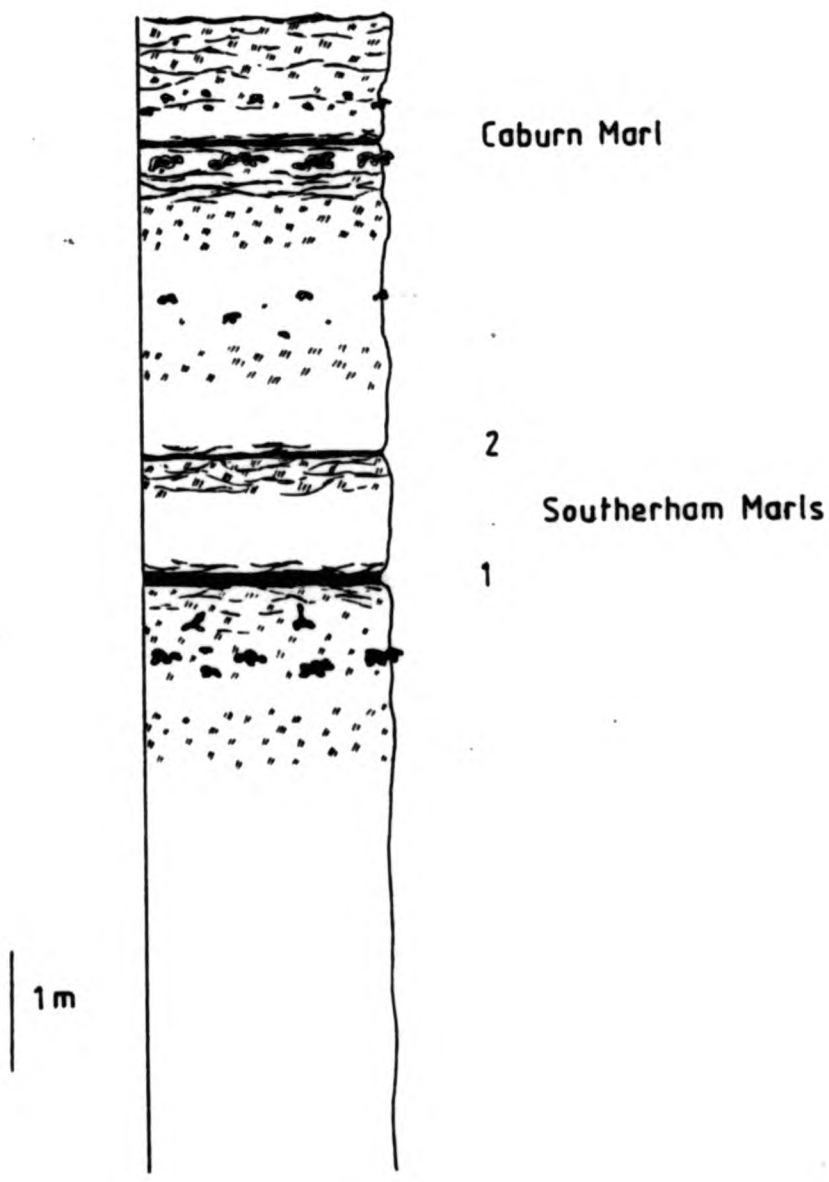


Figure A1.7

NEW PIT DEPOT

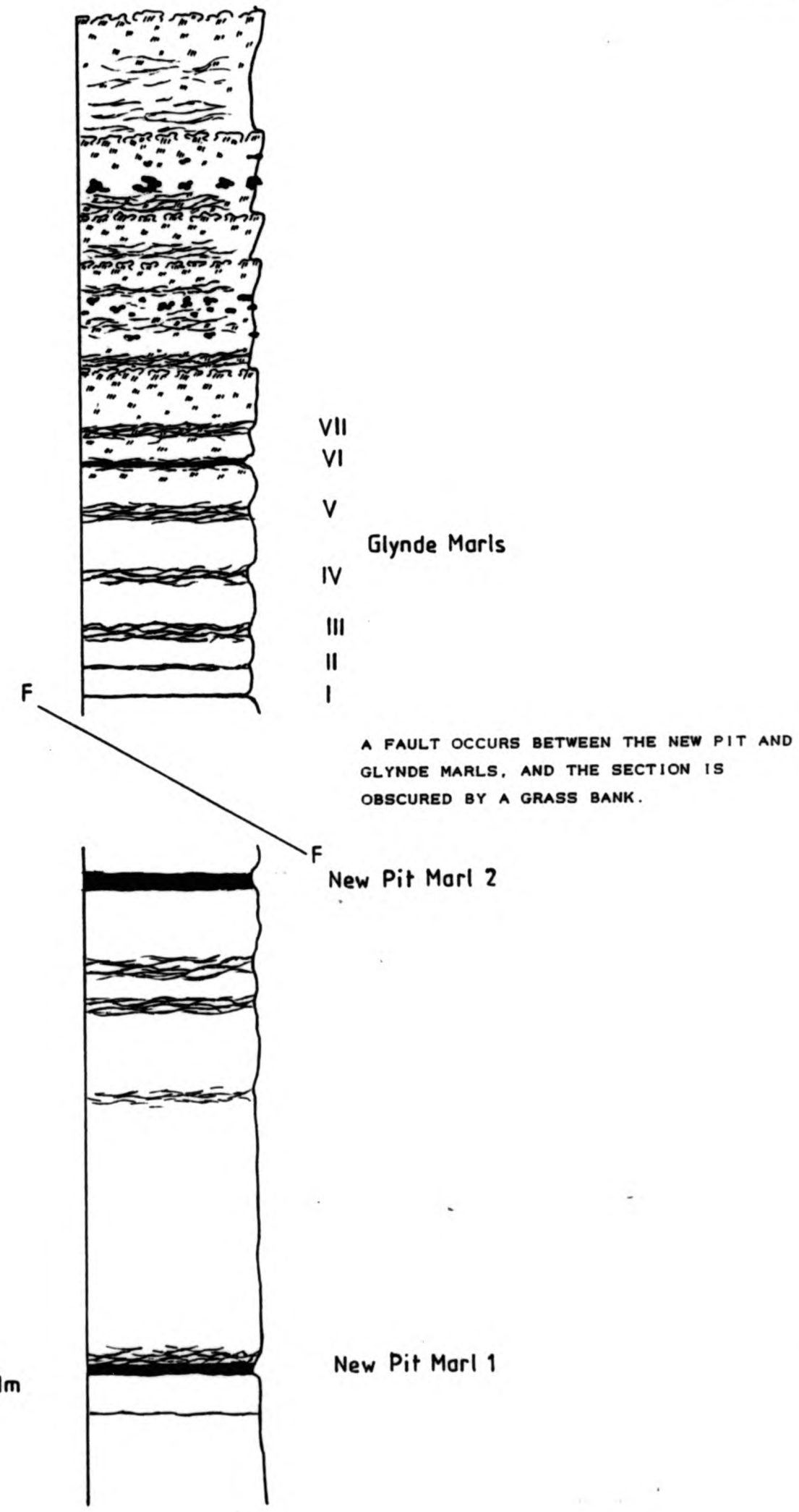


Figure A1.7 cont.

NEW PIT DEPOT

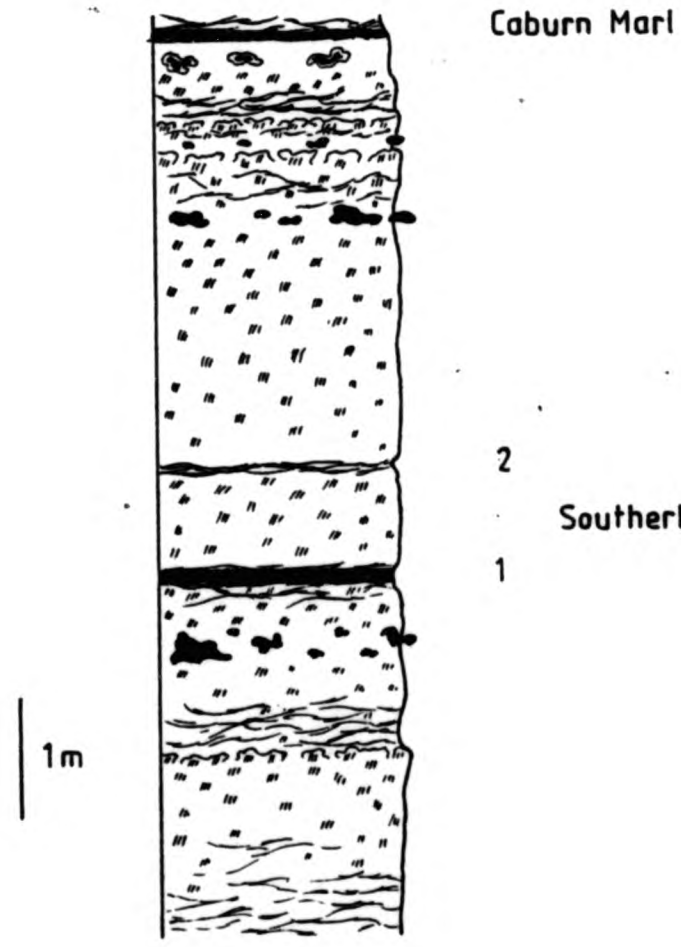


Figure A1.8

BEGGARS KNOLL

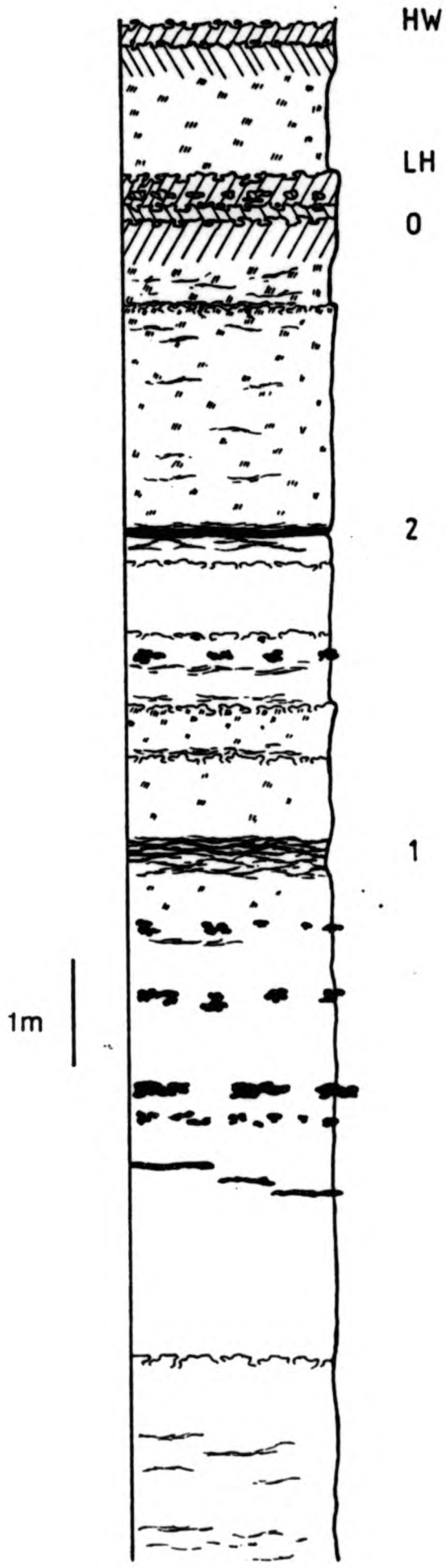


Figure A1.9

BURGHCLERE

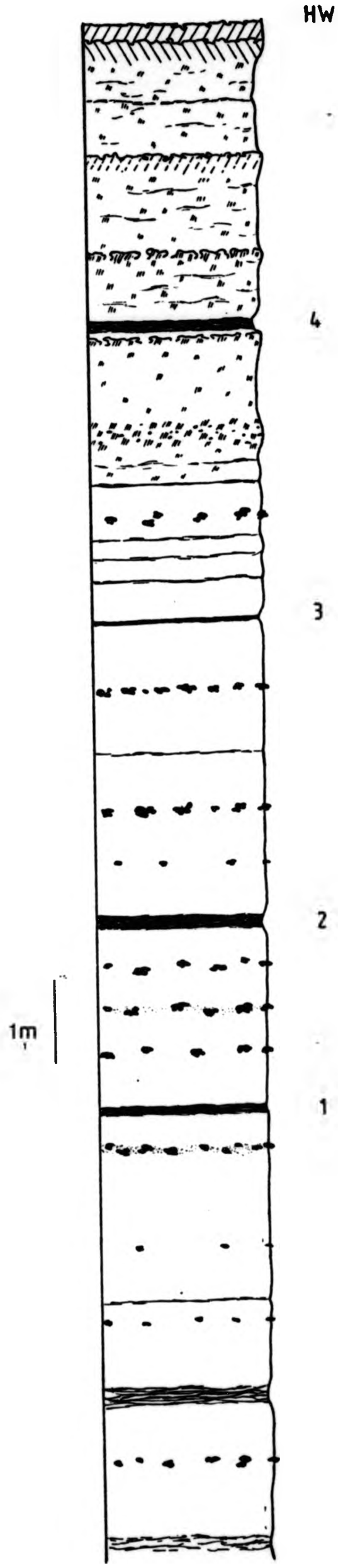


Figure A1.10

COMPTON BAY AND

MILITARY ROAD, I.O.W.

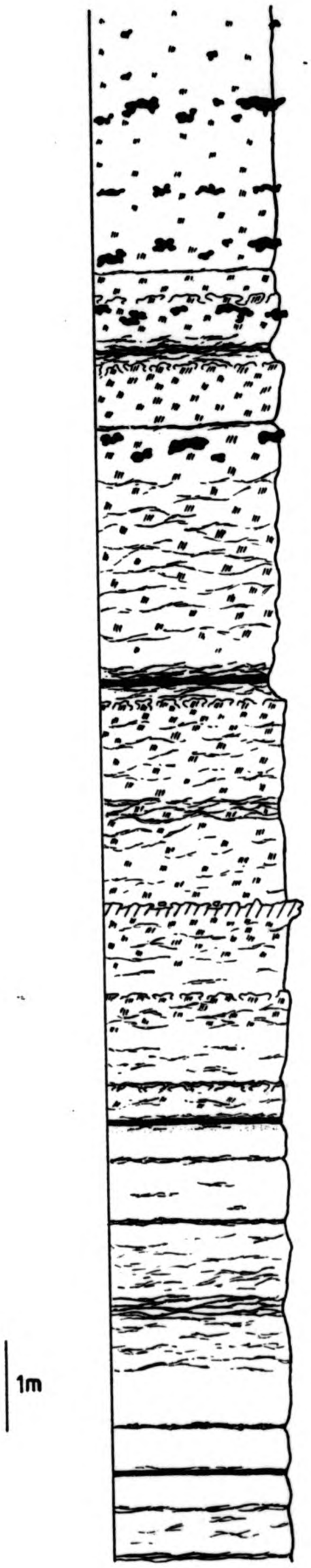


Figure A1.11

EWELME

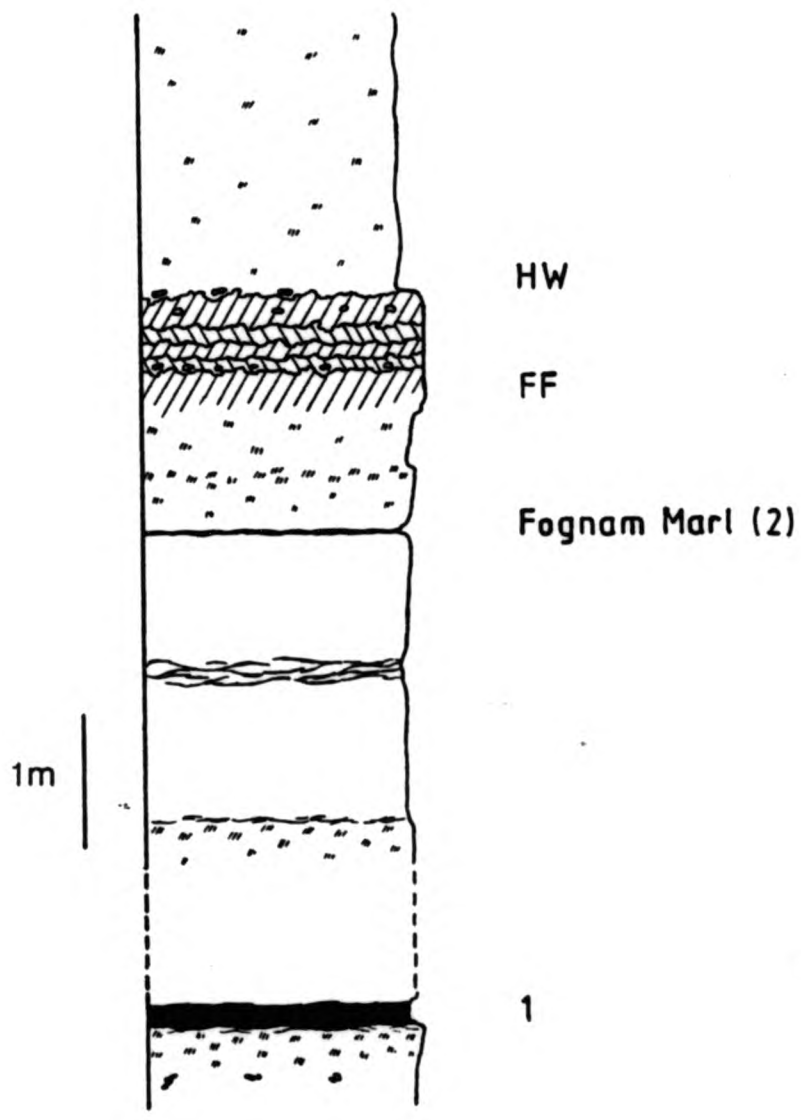


Figure A1.12

FOGNAM FARM

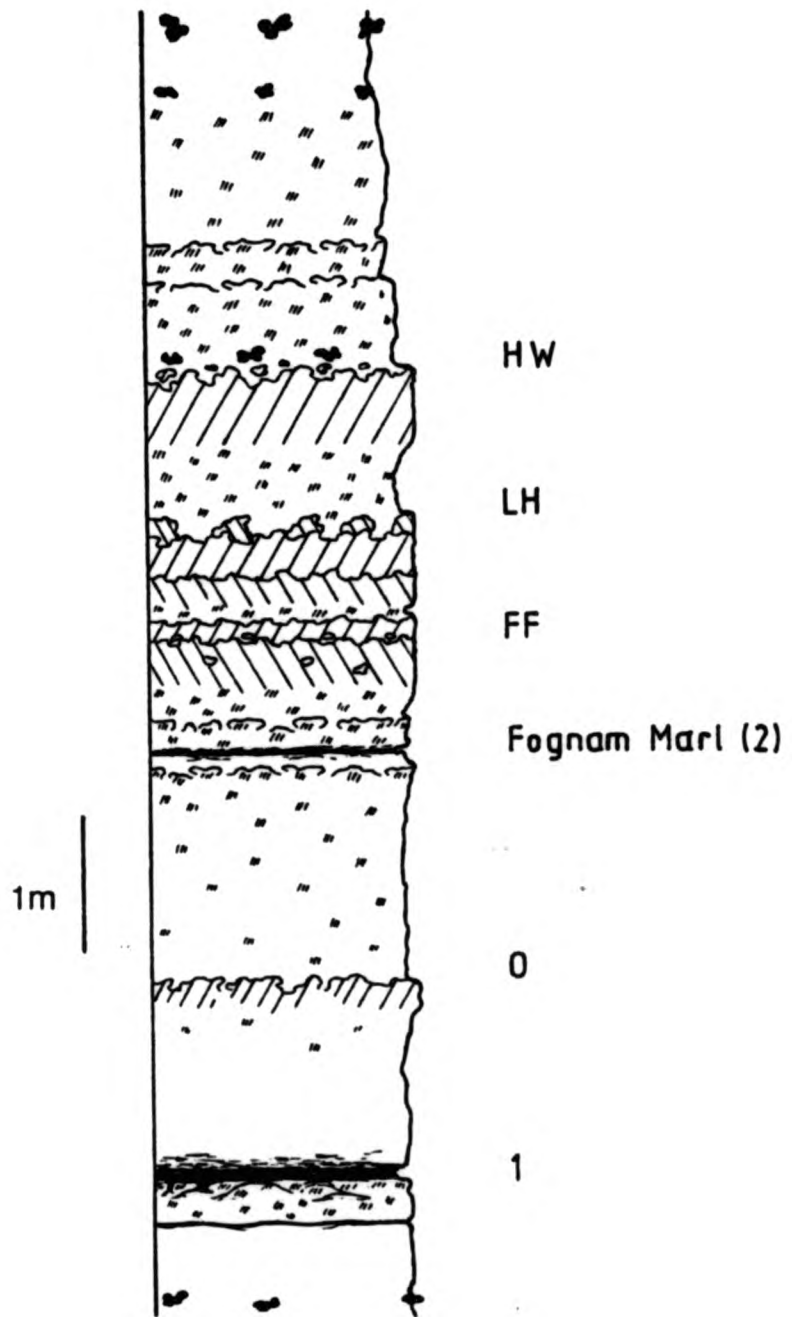


Figure A1.13

KENSWORTH

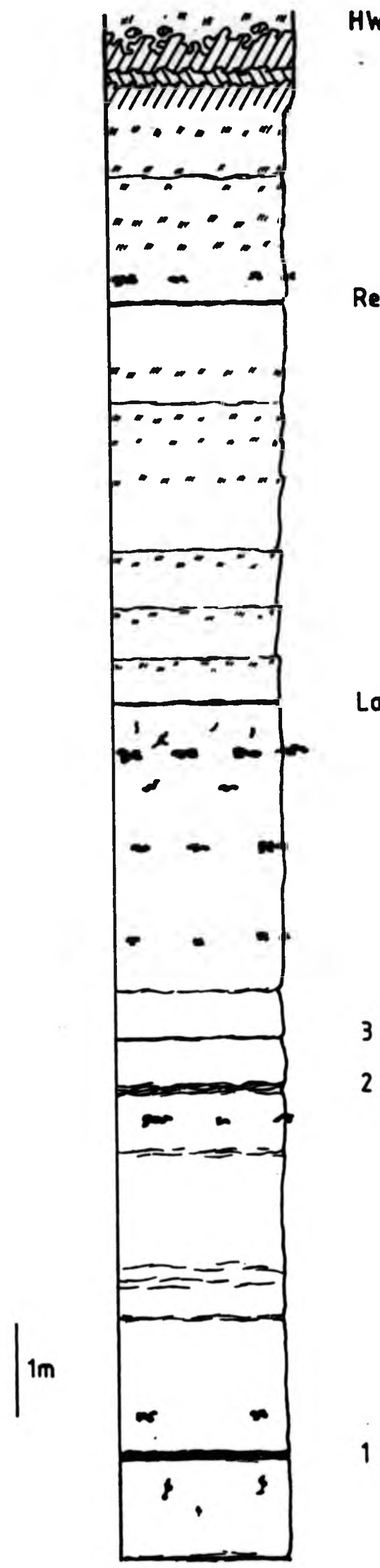


Figure A1.14

SHILLINGSTONE HILL

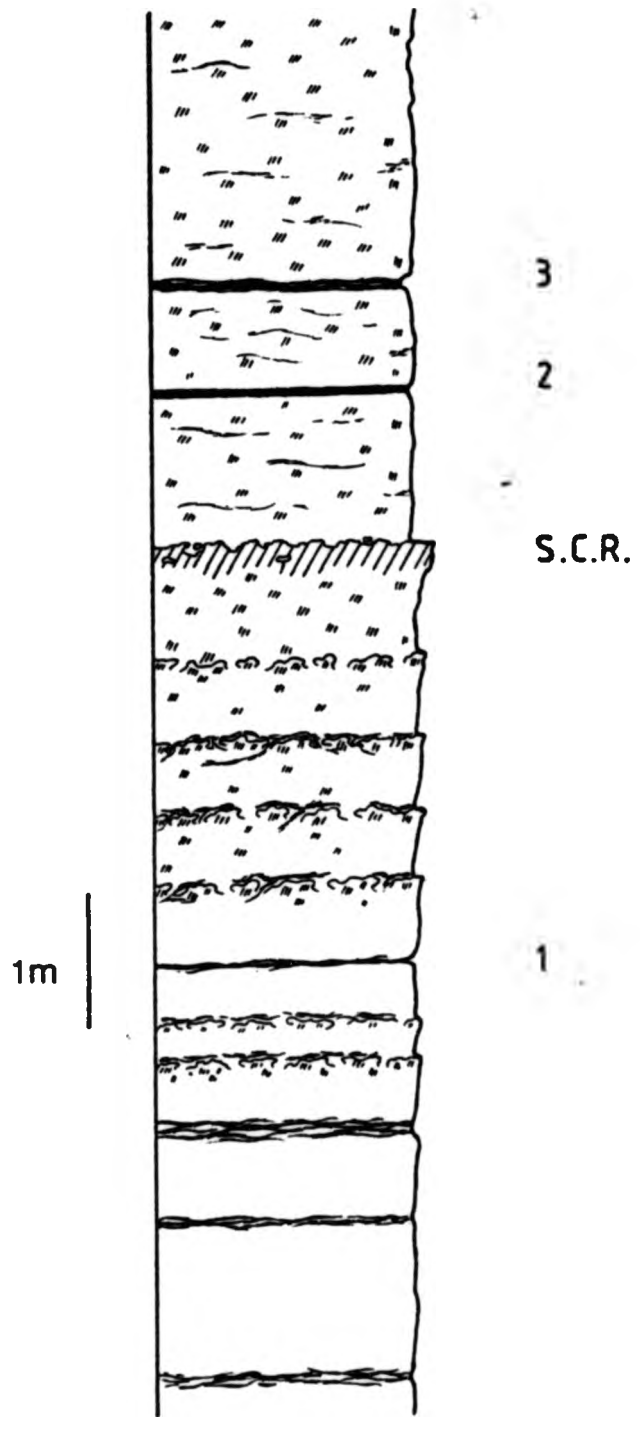


Figure A1.15

BELLEVILLE TO PUYS

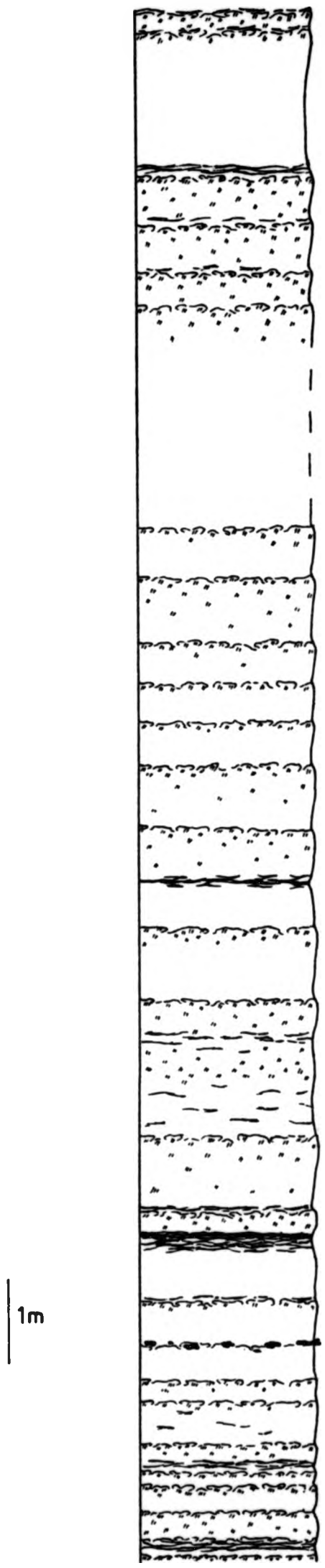
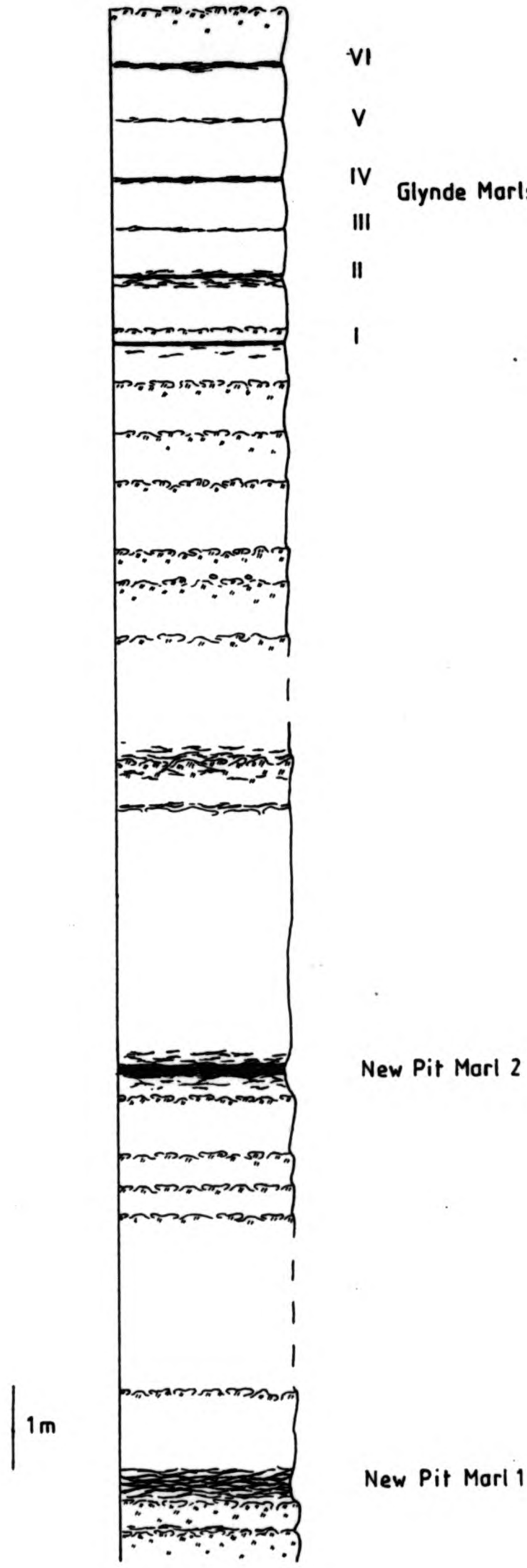


Figure A1.15 cont.

BELLEVILLE TO PUYS



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BELLEVILLE TO PUYS

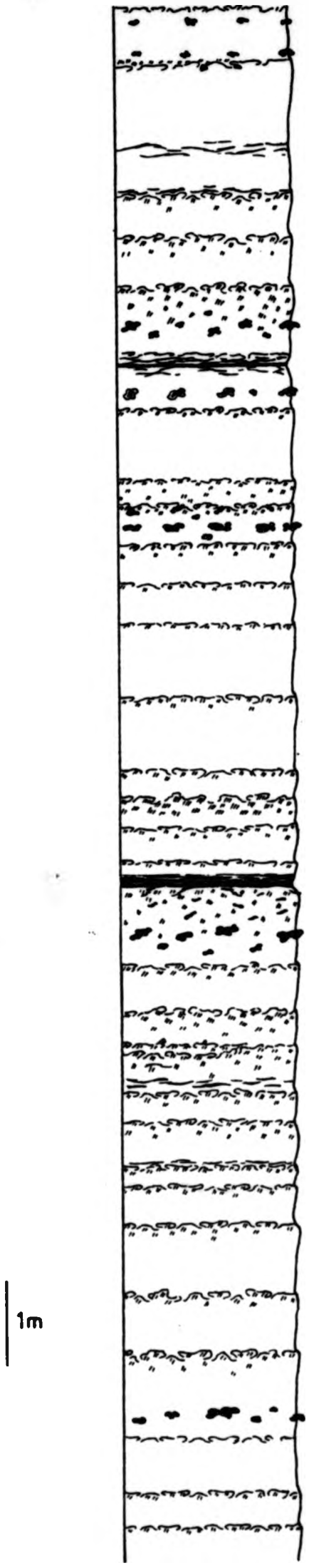
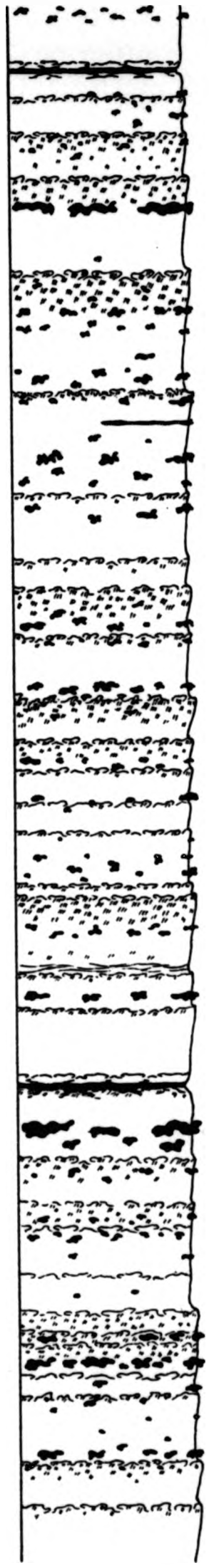


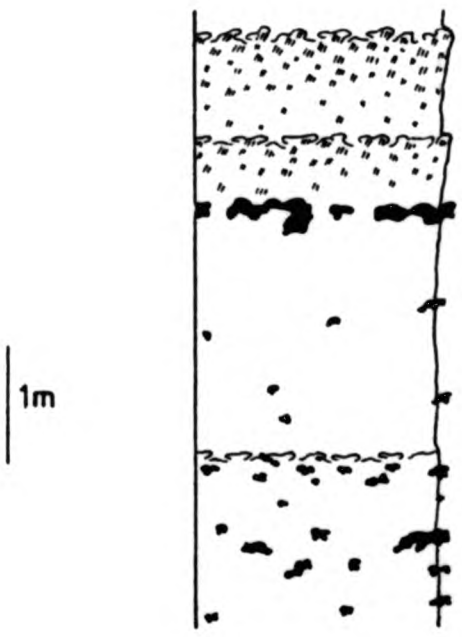
Figure A1.15 cont.



BELLEVILLE TO PUYS

Figure A1.15 cont.

BELLEVILLE TO PUYS



APPENDIX 2

FIELD CHARACTERISTICS OF MIDDLE AND UPPER TURONIAN MARLS

A2.1) INTRODUCTION.

Although marl bands have been widely used in correlation and as marker horizons within individual exposures, there have been relatively few detailed descriptions of the field characteristics of individual bands. The descriptions below give a summary of the salient features of all Middle and Upper Turonian marl bands examined as part of this thesis. Detailed logs of all Middle and Upper Turonian marls are included. The marl bands within and below the Chalk Rock Member will be treated in a separate section. The Appendix ends with brief descriptions of many of the marls found in other parts of the succesion.

A2.2) ANGLO-PARIS BASIN.

A2.2.1) Malling Street Marls (Figure A2.1).

These marls occur at the base of the *Terebratulina lata* Zone of the Middle Chalk.

In Sussex these have only been examined at one locality (Southerham Works Pit), where they are considerably weathered. Two marl bands are seen, of which the upper is the stronger. Malling Street Marl 1 contains a 1 cm to 4 cm thick seam of slightly plastic, greeny-brown, marly chalk. The chalk above and below is non-nodular, classifying it as a type A marl. The upper and lower contacts of the seam appear to be gradational. In comparison, Malling Street Marl 2 has a thicker seam (5 cm to 6 cm) of more plastic marly chalk. The seam is medium to dark grey in colour and has gradational contacts with the white chalk above and below. This marl band is also best classified as a type A.

Mortimore and Pomerol (1987) suggested that, in the North Downs, the Round Down Marl of Robinson (1986) is the lateral equivalent of one of the Malling Street Marls (probably Marl 1, although this is not clear). This correlation is based on the incoming of *T. lata* at this level, combined with geophysical evidence from boreholes. On Akers Steps (Dover) the Marl is flasered and can be classified as either a type C or D marl as nodules are occasionally seen between individual flasers. The thickest flasers occupy a 8 cm thick unit, the upper and lower contacts of this unit are gradational

over at least 10 cm in each direction. Individual flasers can be up to 2 cm thick but most are less than 1 cm, the marly chalk is medium greeny-grey in colour.

On the French coast at Belleville only one marl is seen, Mortimore and Pomerol (1987) suggested that it is the lateral equivalent of Marl 1. The correlation is based on the incoming of *T. lata* at this level, and the presence of flints below the marl, which are comparable to the horizon of occasional flints seen in Glyndebourne Pit (Mortimore, 1986). At Belleville the marl band contains a 6 cm thick seam of marly chalk which at some points becomes thicker and more flasered. Numerous flasers are seen to extend from the seam to a maximum distance of 17 cm. The marly chalk is a light to medium grey in colour and is surrounded by white chalk. Because of the slight variations within the marl seam it is best to classify this marl as a type A/C marl band.

A2.2.2) Lighthouse and Iford Marls.

These two pairs of marls are well developed in places, for example Gun Gardens (Eastbourne) but elsewhere are not apparent at outcrop (Lake *et al.* 1987). These marls have not been examined in detail during this study due to their limited exposure and the dangerous nature of the Gun Gardens section.

A2.2.3) New Pit Marls (Figures A2.2 and A2.3).

These marls occur in the *T. lata* Zone of the Middle Turonian. They occur in a part of the succession which is dominated by relatively uniform white chalk containing minor omission surfaces. Mortimore (1986) reported that abundant *Inoceramus lamarcki* (Parkinson) and *Inoceramus cuvieri* (J. de C. Sowerby) are closely associated with Marl 1 and Marl 2 respectively.

At the type locality in Sussex (New Pit Depot) these marls are only poorly exposed due to faulting, they are better exposed at nearby Caburn Pit and Beachy Head. Mortimore (1983, 1986) recognised three marls; the lower two are very distinctive in the field whilst the third is usually only developed as a weak (type C) flaser marl. Marls one and two have seams which are usually a medium to dark greeny grey colour when fresh, and light grey or greeny-brown when weathered. Mortimore and Pomerol (1987) suggested that in the North Downs, the Warren Marls are the lateral equivalents of the

New Pit Marls. This suggestion is based on a combination of lithological and geophysical evidence from boreholes. They also proposed that it is possible to recognise these marls between Belleville and Puys on the French coast on lithological grounds.

In Sussex the lowest of the three is best classified as a type B/E, and consists of a 6 cm thick marl seam which is often partly flasered. Flasers rise some 35 cm above the top of the marl seam, becoming gradually lighter and thinner upwards. Locally below the base of the seam there is a 7 cm band of weak, white nodules which are surrounded by marly chalk, thin flasers are seen to pass downwards below this to a depth of 6 cm. At some inland sections within Sussex (for example Caburn Pit) the Band is best classified as a type A as it appears much more uniform and lacks the nodular base. At Akers Steps (Dover) the marl band can be classified as a type C, and consists of a 14 cm thick flaser marl overlain by a prominent omission surface. Flasers are generally less than 1 cm thick, but towards the top where they attain a thickness of 1.5 cm. On the French coast between Belleville and Puys it is a type C marl, consisting of a prominent 20 cm thick band of flasers with individuals up to 3 cm thick. The overall colour of the marly chalk is medium grey, white intraclasts or ?burrows can be recognised within flasers

The middle marl band of the three (New Pit Marl 2) is usually the best developed. Characteristically it is a type B·marl containing occasional white chalk intraclasts, with a distinctive erosion surface at the base of the seam. At Beachy Head the marl seam is 11 cm thick, and has at its base a horizon of weakly nodular white chalk intraclasts which varies between 0.5 cm and 9 cm in thickness. Intraclasts also infill thalassinidean burrow systems which penetrate the white chalk below. Flasers pass down from these burrow systems to a depth of at least 15 cm. Occasional white intraclasts are present within the marl seam, although these are generally of small size (1 cm or less). The top surface of the marl seam is unusual in that it is marked by a thin (1 cm), medium grey calcarenitic unit. Only very weak, light grey flasers are seen to rise through the calcarenitic unit, and they quickly grade into the white chalk. At Akers Steps the marl seam is 13 cm thick and is again seen to rest on an erosion surface covered by nodular intraclasts. Small intraclasts are also seen within the marl seam. It can be divided into two parts as the lowest 2 cm of the marl seam is markedly more plastic than the remainder of the seam. At Puys its character is slightly different to that seen in Kent or Sussex as it does

not rest on an erosion surface; it is therefore best classified as a type A. The marl seam is 13 cm thick and is medium brown-grey in colour. Flasers pass downwards 12 cm from the base of the seam. Prominent flasers rise upwards 7 cm from the sharp upper contact, weaker flasers continue upwards for an additional 28 cm. An interesting feature of the Marl at this locality is the presence of both white intraclasts and white burrows within the marl seam.

As noted above, Mortimore (1986) recognised a third (higher) marl. He described this as "a flaser zone rather than a 'closed' seam" and is thus markedly different to the two lower Marls. This 'marl' was not examined in detail in this study due to difficulties in recognising it in inland sections

A2.2.4) Glynde Marls (Figure A2.4).

The Glynde Marls are found approximately two-thirds of the way up the *T. lata* Zone and are often associated with abundant *Inoceramus cuvieri* (Mortimore, 1986). These marls frequently occur just below the incoming of the nodular chalks which characterize much of the remaining Turonian chalk. Mortimore (1987) suggested that these marls are laterally equivalent to the Maxton Marls of the North Downs (Robinson, 1986); the correlation being based on a combination of geophysical and lithological evidence. These marls have also been found between Puys and Belleville on the French coast (Mortimore and Pomerol, 1987); where a sequence of six marls are seen below a succession of nodular units.

This group of marls differs from all others described here as the number of bands can differ markedly between relatively closely spaced exposures. The correlation of many of these bands is at the present time uncertain. To avoid confusion when discussing these units I propose to adopt a system of roman numerals for the numbering of marl bands at each locality. These numerals only apply to the locality in question, similar numbers at different localities do not imply that a correlation exists. In other parts of the text, these marl bands will also have their locality in square brackets [] after the roman numeral to further avoid confusion.

In Sussex, these marls are probably best exposed at Caburn Pit and New Pit. At Caburn Pit six marls can be recognised, with the lowest being the most prominent. Marl I is a type A marl and has a thin (3.25 cm) seam of plastic marly chalk. The colour of the seam is variable; the lower portion (7 mm to 2 cm) of it is dark grey whilst the remainder of the seam is a

grey-brown colour. Below the marl light and medium grey flasers are prominent for 8 cm and continue down for a further 16 cm; above they are seen to rise upwards for 5 cm. Marls II to VI are all type C marls, marl III is the strongest with individual flasers up to 3 cm in thickness. This interpretation differs slightly from Mortimore's (1986) as he only recognised two marls (numbers I and VI). At New Pit Depot (approximately 1 km from Caburn Pit) six marls (I to VI) can again be recognised, the lowest is the most prominent due to its 3 cm thick continuous seam (a type A). Marls II to V consist of flasered marly chalk (type C marls) of variable thickness, marl III being the most prominent. Marl VI is again a type A marl, and has a 4 cm thick seam. Mortimore (1986) proposed that the lowest marl band is equivalent to Marl I at Caburn Pit and the highest is equivalent to Marl VI [Caburn].

In Kent, Robinson (1986) recognised six marls at Dover (Akers Steps) and reported that at inland exposures there may be up to twelve. This differs from Mortimore and Pomerol's (1987, p114) interpretation of the Dover section which shows only two marls. I agree with Robinson's interpretation of the section. Marl I [Dover] is a type C marl and is composed of a 2 cm thick group of thin wispy flasers (individual flasers are usually less than 1 mm thick) which are dark green-grey in colour. Marl II [Dover] is the most prominent of the six and produces a 3 cm wide notch in the cliff. It is a type A marl and has a medium to dark grey seam (light grey when weathered) which is slightly plastic. Flasers pass downwards from the base of the seam to a depth of 7 cm, although little flasering is seen above the marl. Most workers (A. S. Gale *pers. comm*, C. J. Wood *pers. comm*) believe that this marl band is the equivalent of Marl I [Caburn] in Sussex.

Marl III [Dover] is a flaser marl, medium grey in colour, which rests on a nodular unit topped by an omission surface (classifying it as a type E marl). Despite heavy weathering on Akers Steps it can be subdivided using variations in the amount of flasering. Resting directly on the omission surface is a thick flaser (up to 3 cm thick), above this is a 17 cm thick unit with thin, light grey flasers. The 'main' band of flasers is 10.5 cm thick (individual flasers can be up to 3 cm thick), with the lower half containing slightly thicker flasers. Above this is a 9 cm unit of thin, light grey flasers which grade upwards into white chalk.

Marl IV [Dover] is a type C marl, 5 cm to 6 cm thick, with individual flasers less than 1 cm thick. It usually has two or three thick flasers (average thickness 0.5 cm) which are interwoven with thin (less than 1

mm) flasers. The flasers are medium to dark grey in colour when fresh (light grey when weathered) and contain within them occasional white chalk intraclasts.

Marl V [Dover] is best classified as a type E marl. It is well defined, consisting of a 2 cm thick seam of marly chalk which is medium grey in colour (light grey when weathered). Flasers pass up and down from the seam for 4 cm in each direction and the seam rests on weakly nodular chalk.

Marl VI [Dover] is again best classified as a type E marl. The thickest flaser (which can be up to 2 cm thick) rests directly on the nodular unit at the base of the marl band. This flaser is medium to dark grey in colour (lighter when weathered). The flasers above this both thin and lighten in colour with a marked thinning occurring 16 cm above the base. White chalk intraclasts can be recognised within some of the thicker flasers.

On the French coast at Puys, Mortimore and Pomerol (1987) again recognised two marls which they correlated with Glynde Marls I [Caburn] and VI [Caburn] of Sussex. My own observations of the section suggest that it is possible to recognise six marl bands, the highest and lowest being the most prominent (and possibly equal to the two marls documented by Mortimore and Pomerol). Marl I [Puys] has a 4 cm thick seam of medium grey-brown marly chalk, and is best classified as a type A marl. It has thin (1 mm to 3 mm thick) flasers rising 3 cm upwards from the well defined upper contact of the seam and the white chalk.. The lower contact of the seam is sharp and slightly undulating with occasional flasers (up to 1 cm thick) passing downwards into the white chalk. The seam is slightly more plastic at its base which explains the pronounced weathering notch which occurs at its base. When a sample of the marl was examined in the laboratory it was found to have some dark grey patches within it,this suggests that the colour seen in the field may, in part, be due to weathering.

Marl II [Puys] is a type C marl, with light to medium grey flasers, and a total thickness of 10 cm. The flasers are thickest in the centre of the band (up to 3.5 cm thick) and from this level thinner flasers pass upwards and downwards into the white chalk. Intraclasts can be seen within some of the thicker flasers.

Marl III [Puys] is a thin (6 mm thick) type E marl, which consists of medium grey marly chalk. It has very thin (less than 1 mm flasers) passing upwards and downwards (through the surface) from it.

Marl IV [Puys] is a type C marl, the band being 6 cm in total thickness. The flasers are medium grey with the majority being between 1 mm and 3 mm thick.

Marl V [Puys] is another type C marl, consisting of a solitary, 7 mm thick, medium grey flaser. Passing upwards and downwards from it are thin (less than 1 mm thick) flasers.

Marl VI [Puys] differs from the two below it as it is a type E marl. The band is 15 cm thick and consists of thick (up to 3 cm), medium grey flasers, it rests on a unit of weakly nodular white chalk. Within individual flasers it is possible to see variations in the colour of the marly chalk from light to dark grey. Semi-oval intraclasts of white chalk are also seen within some of the thicker flasers.

Possible lateral equivalents of the Glynde Marls are seen at Senneville ($\vec{2}.\overline{14}.$,55,31) further along the French coast, where two marl seams are seen just above the Tillieul Hardgrounds (Mortimore and Pomerol, 1987). The lower (Glynde I [Senneville]) of the two is the more prominent, it is best classified as a type A marl. It consists of a 5 cm to 15 cm thick seam of slightly plastic, medium to dark green-grey marly chalk. Flasers pass downwards 18 cm from the base of the marl seam, thinner ones rise a short distance from its upper contact with the white chalk. The seam does appear to have some internal structure as streaks of darker and lighter material can be seen within the marly chalk. The higher marl of the pair (44 cm above the lower) is a type A/C marl. It consists of a medium to dark grey, slightly flasered seam, which is slightly silty. the seam is 5 cm thick and has prominent thick flasers passing upwards and downwards from it.

A2.2.5) Southerham Marls (Figure A2.5).

In most of southern England two marls are seen, with the lower being the better developed. They are found in the upper third of the *T. lata* Zone and in addition, Mortimore (1986) reports finding *Micraster corbovis* of *lata* Zone type and *Holaster* cf. *subglobosus* between the pair. Two features associated with the lower of the two bands have enabled it to be accurately correlated over much of the Anglo-Paris Basin. Firstly, the band is

underlain by a nodular unit which contains within it thin 'finger' flints. Secondly, within and below the seam the foraminifera *Coscinophragma* is found in flood abundance. Mortimore and Pomerol (1987) proposed that the Langdon Bay Marls in the North Downs were lateral equivalents of these marls, based on geophysical logs and the above pair of diagnostic features. They have also used these same features to show its presence on the French coast between Belleville and Puys.

At Caburn Pit (as in the rest of Sussex) the lower of the two marls (Southerham Marl 1) is the more prominent. It is a type B marl, the seam being up to 12 cm thick. The marly chalk is medium to dark grey when fresh (light browny grey when weathered) and more plastic towards the base. Both the top and bottom of the seam are sharply defined. Flasers from the marl seam penetrate the nodular unit below to a depth of 20 cm. Thinner flasers pass upwards from the top of the seam to a height of 10 cm.

Southerham Marl 2 is a type B/E marl as it has a slightly flasered seam. The marly chalk is firmer than in Marl 1 and is medium to dark grey when fresh (weathering to a light brown colour). The seam is thinner than Marl 1 (at Caburn Pit it is 3 cm thick), but again rests on a nodular unit. The upper and lower boundaries of the seam are more diffuse than the lower marl due to flasering, which extends 30 cm downwards and 10 cm upwards.

At both Langdon Bay and Akers Steps (Dover) Robinson (1986) noted four marls at this height. At Langdon Stairs the lowest and highest of the four are by far the most prominent; the middle two being minor, type C bands. Robinson reported that to the west of Canterbury the middle two marls are absent, and to the west of the Medway only the lowest marl of the four is seen. From the correlation proposed by Mortimore and Pomerol (1987) (based on the evidence cited above) the lowest of the four marls is equivalent to Southerham Marl 1 in Sussex and the highest of the four is equivalent to Southerham Marl 2. This nomenclature will be adopted for the Kent sections in this work, the weak middle two marls being numbered Ib and Ic.

At Langdon Bay, Marl 1 is a type A marl with a 12 cm thick seam, which can be divided into five main units ('a' to 'e'). Unit 'a' is below the base of the main seam, it consists of numerous flasers which pipe down into very weakly nodular chalk (containing 'tubular' flints). Above unit 'a', the lower 3 cm of the marl seam is plastic and medium grey-green in colour (unit 'b'). This grades quickly upwards into a firmer, light brown-grey marly chalk (unit 'c'), which constitutes the bulk of the seam. The top of

the seam is fairly sharp but numerous flasers 'rise' upwards for 5 cm to produce another division (unit 'd'). The highest unit ('e') is one in which only a few light grey flasers are seen within otherwise white chalk. Where these grade into the white chalk defines the top of the marl band.

Marl Ib is a type C marl. It consists of a 7 cm to 10 cm thick band of flasers with individual flasers between 0.25 cm and 2 cm in thickness. The flasers are composed of medium grey, firm marly chalk. Marl Ic, in contrast, is a type D marl, due to the presence of nodules between the flasers. It has a total thickness of 23 cm, although well defined flasers only occupy the middle 15 cm. The colour and texture of the flasers is similar to Marl Ib.

Marl 2 is best defined as a type B marl because it has a sharp base and rests on a weakly nodular unit. The seam is 5 cm to 6 cm in thickness and contains a thin unit of slightly more plastic chalk 1 cm up from the base. The marly chalk is a light brown-grey colour and relatively firm. Flasers pass downwards from the seam, the absolute distance is unclear as the unit of nodular and white chalk below contains numerous thin flasers. The upper contact between the seam and the marly chalk is partly gradational and partly flaserish over approximately 5 cm.

Mortimore and Pomerol (1987) proposed that the lateral equivalent of Marl 1 could be seen on the French coast between Belleville and Puys. This marl has the characteristic finger flints below it and, in addition, abundant *Coscinophragma* within and below it. It is a type A marl and has a 20 cm thick seam. The marly chalk is firm and a medium browny-grey colour. This marl band is also seen further along the coast at Eletot. Here it is both wave-washed and below the water table, the combination of these two features making this possibly the best exposure of the marl within the basin. It is again a type A marl, with a 12 cm thick, medium to dark grey seam. The seam has a sharp upper and lower contacts with the white chalk, flasers 'cut' this contact (upwards 5 cm and downwards 8 cm). The seam is not uniform in colour, there is a 2 cm thick layer approximately 3 cm from the base which is darker and more plastic. Above this layer further streaks of darker material can be seen.

A2.2.6) Caburn Marl (Figure A2.6).

The Caburn Marl is the highest marl seen within the *T. lata* Zone. Mortimore and Pomerol (1987) proposed that in the North Downs the Crab

Bay Marl (of Robinson, 1986) is its lateral equivalent. The evidence for the correlation is based on a combination of geophysical evidence from boreholes and lithological features associated with the marl. Two separate lithological features characterise this marl: beneath it there is usually a carious flint band which, in turn, is underlain by a nodular, sponge rich unit. Using these features, Mortimore and Pomerol (1987) also proposed that this marl is present on the French coast.

In Sussex, at its type locality (Caburn Pit) it is a type A marl. It consists of an 8 cm thick seam of marly chalk, from which flasers pass upwards and downwards into white chalk for approximately 5 cm in each direction. The seam is a light browny-grey colour, plastic, and displays some iron staining. The characteristic flint band is seen 5 cm below the marl seam and the unit of sponge-rich nodular chalk a further 40 cm below.

At Langdon Stairs (Dover) it is a type A/B marl with an 11 cm thick seam. It is classified A/B because there is a thin nodular underlying it whose upper contact is seen both in contact with the seam and 2-3 cm below it. Flasers are again seen to pipe upwards (4 cm) and downwards (3-4 cm) from the marl seam. When fresh the marly chalk is a medium grey colour (light brown when weathered) and slightly plastic. The very 'clean' nature of the marl at this locality shows it to have a sharp base and a slightly gradational top. The accompanying carious flint is seen 11 cm below the base of the marl seam and the iron stained (sponge-rich) nodular unit a further 16 cm.

Between Belleville and Puys (French coast) it is a type A marl, and has a 7 cm thick seam of light to medium grey marly chalk. Thick flasers pipe down from the sharply defined, slightly undulating base to a depth of 10 cm. The upper contact of the seam appears slightly gradational; thick flasers are seen to rise from it to a height of 8 cm, becoming thinner and lighter in colour upwards. Within the seam, occasional glauconitised burrows are visible. At this locality the carious flint is seen 13 cm below the base of the marl seam and the sponge-rich nodular unit a further 50 cm below.

At Eletot, further along the French coast, a possible lateral equivalent of this marl is seen (A. S. Gale *pers. comm.*). It is a 15 cm thick, type C marl, and occurs 14 cm above a prominent nodular unit. The flasers are medium grey when fresh (light browny-grey when weathered) and up to 3 cm in thickness. The density of flasers is variable, the upper 10 cm of the band

having the largest number. Above the band of flasers the chalk is nodular, the degree of nodularity increases upwards.

A2.2.7) Bridgewick Marls (Figure A2.7).

These marls are seen towards the base of the *Holaster planus* Zone (Upper Turonian). They comprise a series of two or three marl bands and are associated with several prominent flint bands (the Bridgewick Flints below Marl 1 and the Bopeep Flints on either side of Marl 2). Mortimore (1986) found abundant *T. lata* and small bivalves (in particular *Spondylus*).In the North Downs, they correlate with the Fan Bay Marls of Robinson (1986) (Bailey *et al.*, 1984). Mortimore and Pomerol (1987) proposed that the lateral equivalents of these marls could be seen on the French coast close to Puys. Evidence for this proposal being based on the lithological similarities of the French and English sections. A tentative correlation with the ME Marl of Lower Saxony (Germany) has been proposed by Wood *et al.* (1984), based partly on the occurrence of a flint maxima at this level (see Mortimore and Wood, 1986).

At the type locality (Bridgwick Pit, Sussex) only two of the Marls are clearly seen (numbers 1 and 2), the third one being very weak (Mortimore 1986). The seam of Marl 1 on one side of Bridgwick Pit rests on a nodular unit (a type B marl), whilst on the other side it rests on white chalk (a type A marl). Its seam is 4 cm thick; the lowest 1 cm of the seam is plastic, the upper 3 cm much firmer. The seam is medium to dark grey in colour when fresh (light grey when weathered) and shows some iron staining. Above the seam there are diffuse flasers which grade into white chalk after approximately 9 cm. Thick flasers (up to 2 cm) of dark grey material are seen to pass downwards from the base of the seam to a depth of 8 cm.

Between Marl 1 and Marl 2 there are several minor bands. Approximately 23 cm above Marl 1 there is a very thin (2 mm) band of firm, medium grey marly chalk (type A) which appears to be continuous across the quarry face. Some 48 cm above this there is an 18 cm thick band of flasers (type D/F). The lowest 8 cm of this unit contains the thickest flasers. The colour of the basal flasers is medium grey, upwards through the unit the colour is seen to lighten. Individual flasers can be up to 5 cm thick and are separated from each other by hard white nodules.. There may be an erosion surface at the bottom of this band, but it is not clearly defined.

Marl 2 is a type B marl, with a 4 cm thick seam of medium grey marly chalk. Flasers pass through the nodular unit below the base of the seam to a depth of 5 cm. The upper contact of the seam is again diffuse, slightly marly chalk is seen up to a height of 7 cm.

Marl 3 is only locally developed (Lake *et al.* 1987, p59) and has only been observed at Shoreham Cement Works. It is a type A marl with an 8 cm thick seam of medium grey chalk. Flasers extend upwards to a height of 7 cm from it, inconsistent ones can be seen to a depth of 27 cm below it.

At Langdon Stairs (Dover) Marls 1 and 2 can be seen, but Marl 3 is missing due to condensation of the chalk at this locality (Mortimore and Pomerol, 1987). Marl 1 has an 8 cm thick seam of marly chalk which is medium to dark grey in colour (streaks of dark grey material are seen within the slightly lighter main body). The base of the seam is sharply defined and rests on nodular chalk, classifying the Marl as a type B. Flasers pass downwards from the base of the seam to a depth of 5 cm (the colour of individual flasers lightens downwards). The seam's upper contact with the white chalk is slightly gradational, and has thin flasers rising from it.

Marl 2 has a 5 cm thick seam composed of dark browny-grey marly chalk. It contains a relatively high percentage of coarse material and it is possible to recognise structure within it due to slight colour variations. The seam base is sharp and well defined, numerous flasers pass downwards from it to a depth of 15 cm. It rests on weakly nodular chalk, suggesting that the Marl is best classified as a type B. The upper contact of the seam is slightly gradational, flasers rise up from it to a height of 5 cm, thinning and lightening upwards. This band varies slightly laterally; in cliff exposures between Langdon Stairs and St Margarets Bay it occasionally becomes flasered and is then best classified as a type F marl.

At Puys, one marl seam is well developed and is believed to be Marl 1 (Mortimore and Pomerol 1987, A. S. Gale *pers. comm.*). Above this (1.30 m) there is a second, weakly developed, type D marl band, which is believed to be Marl 2 (Mortimore and Pomerol, 1987). Marl 1 is a type A marl with a 9 cm thick seam. The marly chalk is firm and is overall a medium grey in colour. The seam contains within it occasional white intraclasts and streaks of darker grey material. Its base is sharp and slightly undulating. Passing down from the base are flasers (to a depth of 25 cm), these decrease in size and number downwards and also lighten. The upper surface of the

seam is slightly gradational, and has thin flasers rising up from it to a height of 9 cm.

Marl 2 at this locality is (as noted above) a type D, consists of an 8 cm thick band of medium grey flasers. the flasers are up to 1 cm thick and are separated from each other by nodular white chalk. Resting on top of this flaser marl is an omission surface.

Marl 2 has also been collected from a small pit near Beauval (north of Amiens). Here it is 8 cm thick and medium grey in colour. The marly chalk is firm to semi-plastic and slightly silty. The marl is best classified as a type B.

A possible equivalent to one of the Marls (A. S. Gale *pers. comm.*) was found at Etretat (further south on the French coast). In the base of some of the channels seen at this locality it is possible to see a very large black flint which has a type A marl 33 cm above it. The marly chalk is light to medium grey, firm, and relatively coarse. The base of the marl seam is undulating but relatively sharp and has flasers passing down from it to a depth of 7 cm. The upper surface is gradational and has thin flasers rising from it to a height of 5 cm

A2.2.8) Lewes Marl (Figure A2.8).

This marl occurs in the middle of the *Holaster planus* Zone. It is characterised in the field on two separate features, firstly the marly chalk is very silty, with a gritty texture when ground between the teeth. Secondly, the flints both below and above the Marl are typically tubular in nature (with an average diameter of 3 cm), having an outer and an inner core of flint which is separated by a "mealy chalky annulus" (Mortimore 1986). Mortimore also noted that the marl seam contains abundant *Micraster leskei* (large forms) and also numerous *Mytiloides striatoconcentricus* (Gümbel) and *M. labiatoidiformis* (Tröger). This marl is not seen at Dover (Bailey *et al.*, 1984; Mortimore, 1986, p113) due to condensation. Mortimore and Pomerol (1987) proposed that its lateral equivalent could be seen on the French coast to the south of Puys. Here, a well defined marl band (containing 'gritty' marly chalk) is seen to rest on white chalk containing tubular flints.

In Sussex, the Marl is well exposed at Navigation Pit where its seam is 7 cm thick, light browny-grey in colour and gritty. Small white chalk intraclasts can be seen within the main body of the marl, towards its base

it becomes partly flasered due to an increase in the number of intraclasts. It is seen to rest on a hard nodular unit which contains the diagnostic tubular flints. It is best classified as a type B/E marl because of its slightly flasered nature. Light grey flasers are seen to pass downwards from the seam into the nodular unit. They are also seen to rise upwards from it to a height of 10 cm and achieve a maximum thickness of 3 cm. At Bridgwick Pit, on the northern side of Mount Caburn, the marl seam is 5 cm thick with similar characteristics to those seen at Navigation Pit.

Although the Lewes Marl is not seen at Dover, it is present in much of the North Downs. Evidence for this was presented by Mortimore and Pomerol (1987) in the form of geophysical logs (p107-109). The absence of any correlation with surface exposures means that its physical characteristics cannot be investigated further.

At Puys, the Marl has a 6 cm thick seam of light to medium grey-green marly chalk. The marly chalk is silty and parts of it are slightly plastic. The seams base is sharply defined and slightly undulating. It is classified as a type A marl, although the presence of intraclasts towards the base of the seam suggest that it may rest on an erosion surface (classifying it as a type B). Prominent flasers are seen to pass downwards from the base of the seam to a depth of 8 cm; thin flasers pass upwards from the top of the seam to a height of 6 cm.

The Marl is also seen at Criel Plage further along the French coast (Mortimore and Pomerol, 1987). Here it is a type A marl with a 14 cm thick marl seam composed of medium brown-grey marly chalk. The seam can be divided into two parts, a lower one, 2 cm thick, which is slightly plastic; and an upper one which is firm. The seam is not uniform in colour, it contains darker streaks within the marly chalk and also occasional white intraclasts. The base of the seam is sharp and has flasers descending into white chalk to a depth of 4 cm. The upper surface of the seam is slightly gradational and has thin flasers rising from it to a height of 8 cm, these flasers lighten in colour upwards. An important feature of the Marl at this locality is the fact that it undulates on a relatively large scale. This was illustrated by Woodroof (1981) in the form of a photograph which showed the base of the marl seam to rise and fall by at least 50 cm over a distance of a few metres.

A2.3) MARL BANDS ASSOCIATED WITH THE CHALK ROCK.

A2.3.1) Introduction.

Bromley and Gale (1982) produced a paper showing a detailed lithostratigraphic correlation between the hardgrounds and marl bands within the Chalk Rock Member at different localities. They gave names to three marl bands seen within and below the Chalk Rock, one marl being associated with each of the Chalk Rock hardground suites. No correlation was made between these marls and those seen in the main part of the Anglo-Paris Basin.

A2.3.2) Fognam Marl.

This marl band is present throughout the area covered by the Chalk Rock with the exception of Wiltshire, where it is cut out by the hardgrounds below it (Bromley and Gale (1982). At Fognam Farm it is a type A marl, with a seam which is 3 cm to 5 cm thick, silty, and plastic. The marly chalk is a medium brown-grey colour and weathers to a light grey-green. The seam has sharp boundaries and rests on soft white chalk which contains light grey flasers. At Ewelme the seam (Figure. 2.11) is 6 cm thick and is markedly more plastic in the centre of the seam. The overall colour of the marly chalk at this locality is a light grey-brown. At the type locality the marly chalk contains scattered glauconite grains and small, glauconitized and phosphatized intraclasts. Mortimore (1987) argued that this marl was the lateral equivalent of the Caburn Marl.

A2.3.3) Latimer Marl.

The description given by Bromley and Gale (1982) of the Marl, at its type locality (Home Farm, Latimer; TQ 005993), suggests that it is a type A marl, with a 10 cm thick seam of light to medium grey marly chalk. Bromley and Gale (1982) reported that the Marl cuts out on the next hardground above the Fognam Farm Hardground. At Kensworth it is again a type A marl, it is 12 cm thick and contains occasional white intraclasts. Mortimore and Wood (1986) proposed that this marl is the equivalent of Southerham Marl 1, based on the presence of scattered 'finger' flints below it and the presence of abundant *Coscinophragma* within it.

A2.3.4) Reed Marl.

At the type locality (Reed) it is a type A marl, with a 2 cm thick, plastic, grey seam. At Kensworth it is again a type A marl, but the seam is slightly thicker (5 cm) and contains light grey, oval burrows. Bromley and Gale (1982) proposed that it is cut out in other sections by the Blounts Farm Hardground. Mortimore and Wood (1986) argued that it is the lateral equivalent of the Caburn Marl.

In addition to the three marl bands described above, several localities display additional marl bands below the Chalk Rock which were not included by Bromley and Gale (1982). The marl seams at these localities are described below.

A2.3.5) Burghclere Road Cutting.

This locality was approximately 0.5 km from the Burghclere locality of Bromley and Gale (1982). It was only accessible during the construction of a new road, and has now been covered over. It did however give an excellent exposure of the Chalk Rock and also revealed four marl bands within and below it (numbered in ascending order 1 to 4). The field characteristics of the lower three marls suggested that they were lateral equivalents of particular marls seen in Kent and Sussex.

Marl 1: A type A marl, with an 8 cm thick seam of firm, medium grey, marly chalk. The base of the seam is flasered, individual flasers continue downwards for up to 9 cm. The upper contact appears gradational. Within the seam some bioturbation could be seen, possible ichnotaxa including *Chondrites* and *Thalassinoides*. Occasional white intraclasts could also be seen. If viewed on its own it would be difficult to suggest a 'Sussex' name for this marl. If however, the other marls in the section are also included it seems likely that this marl is the lateral equivalent of New Pit Marl 1.

Marl 2: Another type A marl, but this time the seam is 20 cm in thickness and more plastic than Marl 1. Flasers pass downwards 6 cm from the base of the seam and are light to medium grey in colour. The marl seam does show poor evidence of bioturbation, probably *Thalassinoides*. It is possible to divide the seam into three parts ('a' to 'c'). The middle part ('b') is slightly darker and more plastic than the ones above and below and contains isolated white burrows. Parts 'a' and 'c' (above and below) are

firmer and lighter, with part 'c' (highest) grading quickly into the white chalk above. As with Marl 1, if this marl is placed in context with the other marls in the section, it may be the lateral equivalent of New Pit Marl 2.

Marl 3: A type A marl but markedly different to Marls 1 and 2. It has a 3 cm thick seam of dark grey-brown, plastic, marly chalk, which grades quickly into the white chalk above and below. Below the seam, occasional flasers extend downwards to a depth of 5 cm. Above the seam proper, where the chalk is still a light grey in colour, it is possible to see occasional lighter burrows. The only marl in Sussex to have a thin and very plastic seam is Glynde Marl I [Caburn], and it is likely that this marl is its lateral equivalent.

Marl 4: This is a type B marl as the lower contact of its seam rests directly on one of the Chalk Rock hardgrounds. The seam is 8 cm to 10 cm thick, and is light to medium grey in colour. The lower half of the seam is more plastic than the upper half. It is difficult to try and allocate a 'Sussex' name to this marl because of the possible condensation associated with the formation of the hardgrounds.

A2.3.6) Beggars Knoll.

At Beggars Knoll, two marls have been found below the Chalk Rock. Marl 1 is a type C marl; it is composed of a 15 cm band of thick flasers underlain by a further 20 cm of thinner, scattered flasers. All the flasers are a light grey colour, and at the upper contact grade quickly into white chalk. The maximum thickness attained by any individual flaser is approximately 4 cm. It is difficult to allocate a 'Sussex' name to this marl.

Marl 2 is a type A marl, it has a 12 cm thick seam of medium grey marly chalk. Although neither the upper or lower contact of the seam is particularly well defined, weak flasers can be seen to pass downwards to a depth of 18 cm. The upper contact of the seam grades quickly into the white chalk above. Mortimore (1987) suggested that this is the lateral equivalent of Southerham Marl 1.

A2.3.7) Ewelme.

Some 3.5 m below the Fognam Marl (described above) a second marl band can be seen. It is a type B marl, with a thick (19 cm) seam of light grey

marly chalk. Flasers are seen to pass downwards from the base of the seam to a depth of 3 cm. The upper contact grades quickly into the white chalk. It is difficult to suggest a name for this marl.

A2.4) MARL BANDS ASSOCIATED WITH THE SPURIOUS CHALK ROCK.

A2.4.1) Introduction.

The Spurious Chalk Rock is a single glauconitized and phosphatized hardground which only occurs in Dorset and on the Isle of Wight. It was initially mapped as part of the Chalk Rock by Strahan (1898). Later work by Rowe (1901, 1908) showed that it occurred lower in the succession than the Chalk Rock and he therefore named it the Spurious Chalk Rock. More recent work (Bromley and Gale, 1982) suggested that it is the lateral equivalent of the lowest widespread hardground of the Chalk Rock, the Ogbourne Hardground. Three localities containing the Spurious Chalk Rock have been examined: Shillingstone Hill in Dorset, and the Military Road and Compton Bay sections on the Isle of Wight.

A2.4.2) Shillingstone.

At this locality, two marls are seen a short distance above the Spurious Chalk Rock, and another marl is seen 2.90 m beneath it.

Marl 1 (below the Spurious Chalk Rock) is a type A/C marl with a total thickness of 5 cm. It consists of a series of interconnecting flasers, each less than 1 cm in thickness, which 'coalesce' in places to produce a uniform, medium to dark grey seam up to 5 cm thick. Mortimore (1987) suggested that this marl is the lateral equivalent of Glynde Marl I [Caburn]

Marl 2 is a type A marl, and contains a 5 cm thick, medium grey-brown seam of plastic marly chalk. Mortimore (1987) suggested that it is the lateral equivalent of Southerham Marl 1.

Marl 3 is a type A marl, and contains a 7 cm thick seam of firm, medium grey marly chalk. At some points numerous white *Thalassinoides* burrows cross-cut the seam, giving it a slightly flasered appearance. Bromley and Gale (1982) tentatively suggested that this marl is equivalent to the Fognam

Marl, whilst Mortimore (1987) suggested that it is the lateral equivalent of Southerham Marl 2.

A2.4.3) Military Road Cutting.

The Spurious Chalk Rock is found towards the base of this heavily air weathered section. A short distance above the hardground two marls are found; the lower one was termed the Black Marl by Rowe (1908) and the upper one the Grey Marl.

The Black Marl is a type A marl with an 5 cm thick, plastic seam. Flasers pass upwards and downwards from the seam and some 20 cm below the seam a nodular omission surface can be found. It was termed the Black Marl because of its characteristic dark colour; however at this exposure the marl was only a medium grey colour, possibly due to air weathering over a long period of time. The Black Marl has also been observed at Five Barrows Pit (SZ 391850) where it exhibits its characteristic colour. It has been proposed by Mortimore and Wood (1986), Mortimore and Pomerol (1987) and Lake *et al.* (1987) that the Black Marl is equivalent to Southerham Marl 1.

The Grey Marl is found 3.8 m above the Black Marl and is best described as a type A/C marl on account of its partly flaserish nature. The seam is 4 cm thick, firm, and a dark to medium grey colour. Numerous flasers pass upwards and downwards from the marl and, like the Black Marl, there is a nodular omission surface a short distance below it. Mortimore and Wood (1986), Mortimore and Pomerol (1987) and Lake *et al.* (1987) suggested that this marl is the lateral equivalent of the Caburn Marl. This correlation is based, in part, on the presence of *Bicavea rotaformis* which is found overlying the Grey Marl (Brydone 1917) and also overlying the Caburn Marl in Caburn Pit and Southerham Works Quarry (Lake *et al.*, 1987, p62).

Above the Grey Marl two further marls can be seen. The first (Marl III) is a type B/D marl consisting of an irregular, slightly flaserish seam set in nodular white chalk. The second (marl IV) is a 5 cm thick type B marl, light grey-green in colour and heavily weathered. A short distance above and below this marl, bands of abnormally large flints are seen. Although Mortimore and Pomerol (1987) presented a log of the Military Road Cutting (p111), it is difficult to correlate the above two marls with it.

A2.4.4) Compton Bay.

Compton Bay is situated below the Military Road Cutting. The Spurious Chalk Rock is again exposed due to folding associated with the Isle of Wight Monocline. Marls above the Spurious Chalk Rock are either inaccessible or deeply cut back in the cliff. It is however possible to collect two marls which occur a short distance below the hardground. Marl 1 is a 6 cm thick type A marl with a sharp base and a slightly flasered upper contact. It is a medium grey colour, partly iron stained and slightly fissile when dry. Marl 2 occurs 1.4 m below the Spurious Chalk Rock. It is a type A marl with a 6 cm thick seam of medium grey, slightly fissile marly chalk. The white chalk below the marl contains an unusually large amount of coarse debris. An additional sample of this marl has been collected from Five Barrows Pit. Although Mortimore and Pomerol's (1987, p111) section is a little unclear, it appears to suggest that this marl is the lateral equivalent of Glynde Marl I [Caburn].

A2.5) BRIEF DESCRIPTIONS OF MARLS FOUND IN OTHER PARTS OF THE SUCCESSION.

A2.5.1) Introduction.

This project has concentrated on marls within the Middle and Upper Turonian, brief descriptions of many of the prominent marls from other stratigraphic heights are described below.

A2.5.2) Lower Turonian.

a) Mead Marls.

A series of up to 6 type B and D marls. They are 5-7 cm thick, firm, silt free, medium green-grey to light green-brown, and may contain white chalk pebbly intraclasts. They are best seen at Holywell, Eastbourne (TV 601968).

b) Holywell Marls.

At Holywell they consist of a series of 6 type A and C marls. They are 4-6 cm thick, firm to slightly plastic and medium grey in colour.

c) Gun Gardens Marls.

A group of three marls. At Gun Gardens (TV 588964) the lower two are type A marls, whilst the highest is a type C. In contrast, at Southerham Works Pit all three are type D marls. They are medium grey to green-grey in colour and may be slightly plastic.

d) Gun Gardens Main Marl.

At Gun Gardens and also at Glyndebourne Pit (TQ 448102) it is a type B marl with a 5 cm seam of medium green-grey, silty and firm marly chalk. By way of a contrast, at Southerham Works Pit it is a type D marl containing flasers up to 0.5 cm in thickness.

A2.5.3) Upper Turonian.

a)South Street Marl.

This marl has been found in Navigation Pit and the adjacent Southerham Works Quarry near Lewes (Sussex), by Mortimore (1986). It is a thin marl (maximum thickness 2 cm in Navigation Pit) and is a medium brown-grey colour. It is best classified as a type A/C marl as it becomes flaserish in parts.

Mortimore and Pomerol (1987) report finding a "local" equivalent of this marl at Bois de Cise. At this locality it is a type B marl and medium grey in colour. Its thickness is variable, at the point of examination it was only 1 cm to 2 cm thick, but it can attain a thickness of 10 cm (A. S. Gale *pers. comm.*).

A2.5.4) Coniacian.

a)Navigation Marls.

Two marls, the lower of the pair is always the more prominent. At Navigation Pit Marl 1 is a type A marl with a 4 cm, brown, slightly plastic seam. Marl 2 is much thinner (less than 1 cm) and is best classified as a type A/C marl. A feature of these marls is the presence between them of carious flints. In Kent, the lateral equivalents of these marls are the Ness Point Marls of Robinson (1986) (Mortimore and Pomerol, 1987) which consist of three very thin type E marls.

b) Beeding Marl.

A type C marl, found slightly above a prominent hardground (Hope Gap Hardground). The marl is medium grey in colour and firm.

c) Shoreham Marls.

A pair of marls with slightly variable characteristics but great lateral continuity. At Shoreham Cement Works Marl 1 is a type A marl with a 3-4 cm thick seam of firm, medium grey, marly chalk. Marl 2 in contrast, is a type C marl with a total thickness of 3 cm. At Seaford Head (TV 498974) the opposite is seen: Marl 1 is a type C marl with a thickness of 20 cm, Marl 2 is a type A marl with a 2 cm thick seam. At Dover (East Cliff) their lateral equivalents were termed the East Cliff Marls by Gale and Smith (1982) (see also Bailey *et al.*, 1983, 1984; Robinson, 1986). As at Seaford Head, Marl 2 is the more prominent of the two (a type A with a 3 cm thick seam), whilst Marl 1 is a poorly developed type C. Robinson (1986) noted that these marls are not present at any inland locality within the North Downs.

d) Belle Tout Marls.

A series of three, thin, type C marls. At Seaford Head, Marl 3 is the best developed having a total thickness of 4 cm and separate flasers up to 1 cm in thickness. The correlation with Kent is a little unclear but the Otty Bottom Marls and Hope Point Marls of Robinson (1986) are probably lateral equivalents.

A2.5.5) Santonian.

a) Buckle Marls.

A series of six type A and C marls, medium grey in colour. They are best seen at Seaford Head. Mortimore (1986) noted that Marl 1 marked the incoming of *Uintacrinus socialis* (Grinnell).

b)Brighton Marl.

A type A/C marl at Seaford Head; the marl band is 5-6 cm thick, flaserish in parts (individual flasers usually less than 1 cm thick), but it may have a seam up to 4 cm thick. The marly chalk is a medium grey colour, and is seen to rest on weakly nodular white chalk.

c) Kemptown Marls.

A pair of type C marls; at Seaford Head the marls are only 3-5 cm thick with flasers generally less than 1 cm thick.

A2.5.6) Campanian.

a) Friars Bay Marls.

Three type C marls. Marl 1 is the best developed at Seaford Head and consists of a 10 cm thick flaserish band with a 'core' of flasers up to 1 cm in thickness.

b) Ovingdean Marl.

A type C marl at Seaford Head, with individual flasers up to 1 cm thick. The marly chalk is a brown-grey colour.

c) Blackrock Marl.

A medium grey, type C marl; flasers can be up to 1.5 cm thick, and can contain fragments of white chalk.

d) Saltdean Marl.

This has only been examined at Seaford Head, where it appears to have been deformed by post-depositional tectonic activity. It consists of a 22 cm thick, type A/C marl band containing a 4 cm thick, medium grey, slightly flaserish seam close to its summit. The flasers below the seam are weak, and often stylolitic. The seam appears to have acted as a slip plane during the post-depositional tectonic activity which affected the area, resulting in thinning of the seam.

e) Rottingdean Pair.

As with the Saltdean Marl, post-depositional tectonic activity has affected the outcrop at Seaford Head, resulting in the near removal of the higher marl. Marl 1 is a type C marl, and consists of a 20 cm thick band of prominent, medium grey flasers.

f) Roedean Triple.

At Seaford Head they are all type C marls, the middle of the three being the most prominent. Marl 1 (lowest) consists of a 12 cm thick band of flasers, individuals generally being less than 2 cm thick. Marl 2 is a 10 cm thick band of thick flasers (individuals up to 4 cm thick) which intertwine in a complex manner. In Marls 1 and 2 there are numerous rounded to sub-angular pieces of white chalk contained within the marly chalk, these may either be intraclasts or distorted burrows. Marl 3 is 7 cm thick; but is only weakly developed in comparison to the other two, consisting of thin flasers which are only a maximum of 0.5 cm thick. All three marls are a medium grey colour.

g) Old Nore Marl.

West of Castle Hill, between Newhaven and Brighton (TQ 445000), this is a type A marl with a 2 cm thick seam of silty, green-grey, marly chalk. Flasers pass upwards 6 cm and downwards 1 cm. At Seaford Head it is slightly thicker with a 7 cm thick seam; however, like some of the other marls at this locality, it has been affected by post-depositional tectonic activity. It was described by Brydone (1914) as the 3" Marl.

h) Old Nore Pair.

Two weak, type C marls, 5-10 cm thick and medium grey in colour.

i)Peacehaven Marl.

A type A/C marl at Seaford Head; the marl band is up to 16 cm thick, flaserish in parts, but may contain a seam up to 2 cm thick. The marly chalk is a medium grey colour and shows good evidence of bioturbation.

j) Meeching Triple.

A series of three weak, type C flaser marls. The bands have a thickness of between 0.5 cm and 4cm, whilst individual flasers are always less than 1 cm thick.

k) Meeching Pair.

A pair of medium grey, type C, flaser marls which occasionally merge, the lower one of the two is the better defined. At Seaford Head, the lower marl and upper marl are 16 and 17 cm thick respectively, whilst individual flasers can be up to 3 cm thick.

l) Telscombe Marls.

A series of four type C and D marls. Marl 1 is the best developed and is a type D marl 1 cm to 2 cm in thickness.

The Castle Hill, Pepper Box, Whitecliff, Portsdown, Scratchell's, Bedhampton, Farlington and Shide Marls were not examined during the course of this study.

APPENDIX 3

METHODS USED IN GEOCHEMICAL DETERMINATIONS.

3.1 POWDER PREPARATION

Between 0.5 and 1 kg of each sample was collected in the field using a hammer and chisel. Every attempt was made to ensure that samples were as fresh and unweathered as possible, and that contamination was kept to a minimum. In the laboratory 100 to 200 g of each sample was carefully inspected and scraped clean with a knife, prior to being placed in a strong plastic bag and carefully disaggregated using a club hammer. Samples from coastal localities were then soaked for a period of at least a week in regularly changed deionised water, in an attempt to remove an salt contamination. All samples were then oven dried, prior to their disaggregation using either a TEMA mill or an agate mortar and pestle. All powders were then stored in clean, airtight glass jars.

3.2 ANALYTICAL METHODS

3.2.1 Lithium metaborate fusion

Each powder were dried at 105°C overnight. 0.2500 g of each was weighed in a disposable plastic weighing boat, and then mixed with 1.2500 g of lithium metaborate (spectroflux). The powder mixture was then transferred to a clean graphite crucible. The crucible was placed in a muffle furnace at 1100°C for 20 minutes to fuse the powders. After the allotted time the melt was tipped from the crucible into a plastic bottle on a magnetic stirrer containing 3.5% nitric acid; this mixture was then stirred until all the fused material had dissolved (30 mins. to 1 hour). The solution was then filtered to remove any carbon particles (derived from the crucible) using a fast filter paper (Whatman No. 41), and made up to 250 ml using deionised water. The made-up solution was then transferred to a new 250 ml plastic bottle, stored within a refrigerator and analysed within four days in order to avoid the possibility of the metastable silica precipitating.

3.2.2 Hydrofluoric and perchloric acid digestion

Each powder was dried at 105°C overnight. 0.500 g of each was weighed and transferred to a clean 60ml PTFE beaker and moistened with 4-5 ml of deionised water. 10 ml of 48% HF (AnalaR concentrated hydrofluoric acid) and 8 ml of 60% $HClO_4$ (AnalaR concentrated perchloric acid). The PTFE beaker was then placed on a hotplate at approximately 230°C until the decomposed sample reached near dryness, at which point the above process was then repeated. After the second digestion the sample was carefully inspected for evidence of undigested material, if any was present the above process was repeated for a third time. When fully digested, 5 ml of 60% $HClO_4$ was added and the sample again evaporated to near dryness. 10 ml of 5M nitric acid was then added, and the sample warmed gently on a hotplate until digested. The sample was then cooled, transferred to a 50 ml volumetric flask, and made to volume with deionised water. It was then transferred to a new 60 ml plastic bottle and stored.

3.2.3 Acid digestion followed by separation of the REE's using ion exchange columns

This method is identical to that of Jarvis and Jarvis (1985). The acid digestion was carried out using a $HF/HClO_4$ digestion similar to the one described above, except that 4 ml of saturated boric acid (AnalaR) was added at the same time as the final 5 ml of $HClO_4$ in order to remove any traces of HF, and 10 ml of 6N Hydrochloric acid was added instead of the nitric acid. Separation was achieved using 25 cm columns of 2 cm diameter packed with 12 cm of Dowex® AG 50W-X8 (200-400 mesh) ion exchange resin.

3.2.4 Acetic acid digestion

Each powder was dried at 105°C overnight. 0.500 g of powder was placed in a 150 ml glass beaker, into which was also added 75 ml of acetic acid buffered to pH 5 with sodium acetate (136 g of AnalaR hydrous sodium acetate, plus 36.25 ml of AnalaR glacial acetic acid, and made up to 1 litre with deionised water). The beaker was then placed in an ultrasonic tank for one hour to ensure complete dissolution. The solution was then passed through a slow filter (Whatman No. 50) to remove any insoluble material, made up to 100 ml with deionised water, and stored in a clean plastic bottle (100 ml).

3.3 ANALYTICAL CONDITIONS

3.3.1 Method

Analyses have been carried out on an ARL 3510 Inductively Coupled Plasma Atomic Emission Spectrophotometer based in the School of Earth Sciences at Thames Polytechnic. With the exception of solutions prepared using lithium metaborate fusion, matched synthetic standards were used for calibration, with rock standards being analysed to check on accuracy. For lithium metaborate fusions, 'natural rock' standards of similar compositions were used due to the complex nature of matrix. The rock standards used were: ZGI/KH (limestone), ZGI/TB (slate), NBS1b (argillaceous limestone), NBS1c (argillaceous limestone), NBS120b (phosphate rock), MESS 1 (marine sediment) and BCSS 1 (marine sediment).

The analytical lines used were either those recommended by Thompson and Walsh (1983, p89 & 96), or those recommended by Jarvis and Jarvis (1988).

To minimize effects caused by differences in the matrixes of the synthetic standards and the 'unknown' rocks, background correction was applied during analysis. In order to correct for machine drift during analysis a monitor solution containing all the elements was analysed after every five samples, any drift being corrected on a spreadsheet at a later date. In an attempt to ensure comparable results between batches a number of the samples from the first batch analysed were included in every subsequent batch, corrections then being applied if differences were observed. In addition to this, the composition of the synthetic or natural standards remained constant for all batches in a further attempt to ensure homogeneity.

When analysing for REE, six major elements were also determined (Ba, Ca, Fe, Sr, Ti and Zr) in order to correct for interferences on the REE caused by the small and variable amounts of the latter which by-pass the cation exchange proceedure (see Jarvis and Jarvis, 1988).

3.3.2 ICP-AES operating conditions

Operation:	Sequential
Nebulizer type:	Meinhard (pumped using peristaltic pump)
Injector gas flow	1l min^{-1}
Sample uptake rate:	2ml min^{-1} (except REE analysis)
Sample uptake rate:	200µl min^{-1} (REE analysis)
Power input:	1.5kW

3.3.3 Wavelengths and detection limits for REE analyses

Element	Wavelength	Detection limit ($\mu g\ g^{-1}$)
La	398.85	0.087
Ce	418.66	0.29
Pr	422.29	0.13
Nd	430.36	0.17
Sm	359.26	0.062
Eu	381.97	0.009
Gd	335.05	0.069
Dy	353.17	0.022
Ho	345.60	0.019
Er	390.63	0.037
Yb	328.94	0.008

Lu	261.54	0.007

Detection limits are equal to ten times the standard deviation at the analytes wavelength and are reported in 'rock values' (10x dilution)

3.3.4 Wavelengths used and detection limits for major and trace element determinations

Element	Wavelength		Detection limits	
		as sprayed	trace[1](100x)	major[2](1000x)
		(µg g^{-1})	(ppm unless •)	
Al	308.215	0.15	2.83x10^{-3}•	0.0283•
Ba	455.403	0.02	2	
Ca	422.673	0.015	2.1x10^{-4}•	2.1x10^{-3}•
Cr	205.552	0.01	1	
Cu	324.754	0.01	1	
Fe	273.955	0.02	2.86x10^{-4}•	2.86x10^{-3}•
K	766.491	0.5	6.03x10^{-3}•	0.0602•
Li	670.78	0.015	1.5	
Mg	279.08	0.25	4.15x10^{-3}•	0.04146•
Mn	294.92	0.025	3.23x10^{-4}•	3.23x10^{-3}•
Na	589.592	0.1	1.35x10^{-3}•	0.0135•
Ni	231.604	0.02	2	
P	178.287	0.1	2.29x10^{-3}•	0.0229•
Sc	361.384	0.005	0.5	
Si	251.611	0.05	1.07x10^{-3}•	0.0107•
Sr	346.446	0.1	10	
Ti	337.28	0.05	8.34x10^{-4}•	8.34x10^{-3}•
V	311.07	0.02	2	
Y	371.03	0.01	1	
Zn	213.856	0.005		0.5
Zr	339.2	0.01	1	

Limits are based on 10 times the standard deviation of the background emission at the analytes wavelength. The precision at LQD is ±10%

• Detection limit calculated in oxide weight percent.

1 'Rock value' detection limits for trace element and acetic acid dissolution analyses (100 times dilution).

2 'Rock value' detection limits for major element analyses (1000 times dilution).

3.4 PREPARATION FOR XRD ANALYSIS

Insoluble residues for XRD analysis were prepared by dissolving approximately 50 g of chalk (white or marly) in approximately 250 ml of 1M acetic acid. If all the acid was used up (checked using a pH meter), and carbonate was still visible, it was poured away and replaced with a further 250 ml of 1M acetic acid.

Once all the carbonate had been removed, the remaining insoluble material was washed repeatedly using deionised water. The residue was then centrifuged for 15 minutes, and the clay fraction removed and smeared on a glass slide using the method of Croudace and Robinson (1983).

3.5 STABLE ISOTOPE ANALYSIS

Liberation of CO_2 for analysis was achieved by reacting 2 ml of anhydrous 100% phosphoric acid with approximately 3 mg of dried sample at 25°C, using a method similar to described by McCrea (1950). The gas was analysed on a VG Isogas SIRA 12 Mass Spectrometer at the Department of Earth Sciences, Liverpool University. Standard correction procedures were employed and the results expressed as per mil (‰) deviations from the PDB international standard (Craig, 1957).

APPENDIX 4

GEOCHEMICAL DATA USED IN THIS STUDY

All powders used in this study have been catalogued and are stored at the School of Earth Sciences, Thames Polytechnic.

Please note: N.D. either signifies that the quantity of an element in a sample was below the detection limit of the machine being used, or that the element was not determined in the sample.

Sodium was not determined in any samples because of the possibility of salt contamination in samples collected from coastal localities.

A4.1 MARLS FROM THE ANGLO-PARIS BASIN.

A4.1.1 Malling Street Marls.

	S.W.1	S.W.2	D.2
SiO_2	16.95	17.49	5.33
Al_2O_3	5.382	5.032	1.210
Fe_2O_3	2.066	1.102	0.319
MnO	0.024	0.027	0.023
MgO	1.310	1.097	0.527
CaO	39.93	41.38	48.16
Na_2O	N.D.	N.D.	N.D.
K_2O	1.091	0.875	0.251
TiO_2	0.533	0.211	0.053
P_2O_5	0.552	0.268	0.123
Ba	79.6	64.1	24.9
Cr	N.D.	7.1	N.D.
Cu	19.2	18.6	0.8
Li	20.0	16.6	23.1
Ni	40.7	9.4	N.D.
Sc	4.06	4.00	1.40
Sr	413	416	435
V	57.6	34.2	9.2
Y	27.8	18.5	9.1
Zn	125.9	49.7	21.8
Zr	48.8	24.0	2.5

S.W.1 & 2 = Southerham Works Pit, Marls 1 and 2

D.2 = Malling Street Marl 2, Akers Steps, Dover (Round Down Marl of Robinson, 1986)

Major elements expressed in oxide weight percent, trace elements in parts per million.

N.D. = not determined.

A4.1.2 New Pit Marl 1.

	D	C	B	P	NP
SiO_2	6.14	9.307	10.66	6.504	N.D.
Al_2O_3	2.059	2.461	2.754	1.725	2.946
Fe_2O_3	0.555	0.556	0.561	0.424	0.679
MnO	0.029	0.032	0.030	0.029	0.031
MgO	0.708	0.676	0.815	0.568	0.766
CaO	45.34	44.43	44.36	50.26	48.30
Na_2O	N.D.	N.D.	N.D.	N.D.	N.D.
K_2O	0.382	0.401	0.493	0.328	0.444
TiO_2	0.103	0.130	0.137	0.088	0.149
P_2O_5	0.179	0.155	0.163	0.107	0.166
Ba	41.1	48.6	56.0	58.3	35.0
Cr	6.3	6.5	8.5	11.9	N.D.
Cu	1.6	1.7	3.4	1.0	9.35
Li	23.1	15.1	11.5	10.8	12.0
Ni	N.D.	N.D.	3.6	N.D.	6.3
Sc	1.92	2.49	2.65	1.80	2.92
Sr	559	620	627	627	583
V	17.6	18.7	19.4	13.5	20.1
Y	12.2	12.1	13.0	10.4	13.2
Zn	27.4	29.4	38.2	18.6	40.7
Zr	5.4	3.8	8.4	6.8	8.1

D = Akers Steps, Dover.

C = Caburn Pit, Sussex.

B = Beachy Head, Sussex.

P = Between Puys and Belleville on the French coast.

NP = New Pit Depot, Sussex

Major elements expressed in oxide weight percent, trace elements in parts per million.

N.D. = not determined.

A4.1.3 New Pit Marl 2.

	D	C	B	P	NP
SiO_2	7.570	11.90	12.65	8.766	N.D.
Al_2O_3	2.230	3.340	3.436	2.429	3.881
Fe_2O_3	0.599	0.665	0.714	0.482	0.750
MnO	0.025	0.032	0.028	0.030	0.034
MgO	0.797	0.905	1.016	0.707	1.016
CaO	48.45	42.50	42.51	46.32	45.32
Na_2O	N.D.	N.D.	N.D.	N.D.	N.D.
K_2O	0.389	0.480	0.601	0.438	0.502
TiO_2	0.086	0.138	0.151	0.093	0.159
P_2O_5	0.153	0.151	0.147	0.089	0.159
Ba	39.5	55.7	63.5	111.0	36.4
Cr	N.D.	N.D.	15.6	7.4	16.6
Cu	6.0	3.5	4.5	1.0	10.2
Li	N.D.	14.4	20.2	14.4	18.4
Ni	N.D.	1.2	4.7	5.4	8.6
Sc	2.04	3.00	3.04	2.07	3.08
Sr	573	582	576	588	459
V	18.2	20.1	24.7	14.3	23.5
Y	11.4	12.6	12.5	10.1	13.3
Zn	26.7	32.3	46.3	32.9	48.2
Zr	3.8	5.1	11.2	9.0	18.1

D = Akers Steps, Dover.

C = Caburn Pit, Sussex.

B = Beachy Head, Sussex.

P = Between Puys and Belleville on the French coast.

NP = New Pit Depot, Sussex

Major elements expressed in oxide weight percent, trace elements in parts per million.

N.D. = not determined.

A4.1.4 Glynde Marls; Akers Steps, Dover.

	I	II	III	IV	V	VI
SiO_2	N.D.	25.98	N.D.	N.D.	8.42	N.D.
Al_2O_3	0.494	7.950	1.833	0.924	2.595	2.023
Fe_2O_3	0.149	1.568	0.444	0.249	0.609	0.470
MnO	0.026	0.016	0.030	0.026	0.026	0.024
MgO	0.355	2.897	0.630	0.444	0.942	0.676
CaO	51.38	32.24	46.73	49.26	44.27	45.85
Na_2O	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
K_2O	0.114	0.285	0.335	0.182	0.331	0.344
TiO_2	0.021	0.235	0.074	0.037	0.136	0.103
P_2O_5	0.070	0.139	0.138	0.109	0.148	0.251
Ba	15.4	25.9	38.2	28.0	32.7	38.9
Cr	N.D.	5.0	0.6	0.7	3.8	4.3
Cu	1.1	16.1	1.4	2.1	2.8	1.9
Li	14.2	N.D.	20.2	21.7	34.4	31.4
Ni	N.D.	21.5	N.D.	N.D.	0.2	N.D.
Sc	N.D.	1.78	1.59	1.06	1.44	1.67
Sr	665	438	626	694	528	652
V	5.3	24.9	17.1	8.2	16.9	15.7
Y	6.8	15.9	11.0	8.4	9.6	14.5
Zn	23.3	79.9	36.0	19.0	30.2	38.1
Zr	5.2	303.1	3.7	6.4	8.4	4.4

Major elements expressed in oxide weight percent, trace elements in parts per million.

N.D. = not determined.

A4.1.5 Glynde Marls; Puys, French Coast.

	I	II	III	IV	V	VI
SiO_2	11.40	N.D.	N.D.	N.D.	N.D.	N.D.
Al_2O_3	3.185	1.862	0.977	0.879	1.120	1.123
Fe_2O_3	0.552	0.484	0.329	0.322	0.301	0.322
MnO	0.025	0.025	0.028	0.025	0.027	0.028
MgO	0.780	0.611	0.440	0.443	0.467	0.522
CaO	48.13	46.27	53.63	53.33	51.58	52.29
Na_2O	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
K_2O	0.357	0.386	0.204	0.176	0.230	0.219
TiO_2	0.110	0.077	0.044	0.038	0.047	0.058
P_2O_5	0.120	0.127	0.122	0.070	0.087	0.128
Ba	96.9	69.9	35.0	31.4	41.9	30.3
Cr	N.D.	5.4	N.D.	6.9	N.D.	8.1
Cu	3.2	0.6	N.D.	N.D.	N.D.	N.D.
Li	32.7	12.3	7.7	11.8	10.1	12.2
Ni	9.9	4.7	N.D.	N.D.	N.D.	N.D.
Sc	1.43	1.64	1.01	0.90	0.99	1.25
Sr	561	618	671	655	648	634
V	19.6	20.8	10.9	9.3	10.3	10.6
Y	11.7	10.3	7.8	7.0	7.3	8.3
Zn	41.9	33.5	20.6	44.7	16.0	16.1
Zr	17.9	3.5	4.1	4.2	3.8	4.5

Major elements expressed in oxide weight percent, trace elements in parts per million.

N.D. = not determined.

A4.1.6 Glynde Marls, Sussex.

	C	NP
SiO_2	33.28	N.D.
Al_2O_3	10.569	4.909
Fe_2O_3	1.622	0.918
MnO	0.013	0.023
MgO	2.715	1.506
CaO	23.97	43.69
Na_2O	N.D.	N.D.
K_2O	0.639	0.406
TiO_2	0.349	0.166
P_2O_5	0.159	0.125
Ba	57.3	23.7
Cr	3.3	N.D.
Cu	6.1	12.7
Li	80.3	47.3
Ni	29.1	13.8
Sc	3.50	2.05
Sr	315	458
V	47.7	26.0
Y	12.1	11.1
Zn	71.3	58.9
Zr	62.1	38.6

C = Glynde Marl I [Caburn]

NP = Glynde Marl I [New Pit]

Major elements expressed in oxide weight percent, trace elements in parts per million.

N.D. = not determined.

A4.1.7 Southerham Marls; Dover.

	DA.1	DA.2	DL.1	DL.2
SiO_2	17.95	11.14	N.D.	N.D.
Al_2O_3	4.904	4.231	5.453	4.580
Fe_2O_3	1.168	0.142	1.273	1.435
MnO	0.023	0.030	0.025	0.025
MgO	2.059	1.439	2.084	1.487
CaO	36.97	38.05	37.20	41.58
Na_2O	N.D.	N.D.	N.D.	N.D.
K_2O	0.343	0.709	0.486	0.879
TiO_2	0.165	0.539	0.189	0.554
P_2O_5	0.113	0.185	0.085	0.201
Ba	28.1	52.3	32.4	59.6
Cr	N.D.	N.D.	N.D.	14.2
Cu	1.9	2.1	3.2	4.6
Li	133.5	57.4	N.D.	45.2
Ni	12.0	19.4	14.5	15.7
Sc	1.70	3.36	2.05	3.61
Sr	610	612	594	590
V	18.4	60.7	20.6	61.2
Y	18.7	14.3	20.5	15.9
Zn	75.4	57.9	106.5	68.9
Zr	16.3	13.4	94.7	43.8

DA.1 & 2 = Marls 1 & 2 from Akers Steps, Dover (Langdon Bay Marls 1 & 4 of Robinson, 1986).

DL.1 & 2 = Marls 1 & 2 from Langdon Stairs, Dover (Langdon Bay Marls 1 & 4 of Robinson, 1986).

Major elements expressed in oxide weight percent, trace elements in parts per million.

N.D. = not determined.

A4.1.8 Southerham Marls; Sussex and French coast.

	C.1	C.2	Puys	Eletot
SiO_2	18.90	9.60	19.71	21.37
Al_2O_3	5.656	2.260	5.127	6.102
Fe_2O_3	1.050	0.584	1.155	1.322
MnO	0.023	0.027	0.25	0.25
MgO	1.801	0.738	1.778	2.987
CaO	37.67	45.65	37.93	37.77
Na_2O	N.D.	N.D.	N.D.	N.D.
K_2O	0.454	0.378	0.397	0.470
TiO_2	0.204	0.196	0.178	0.200
P_2O_5	0.080	0.122	0.071	0.073
Ba	38.8	39.2	72.3	31.2
Cr	2.8	N.D.	N.D.	N.D.
Cu	4.1	2.8	0.5	N.D.
Li	54.4	17.4	95.6	251.6
Ni	21.1	3.8	18.9	32.0
Sc	2.28	1.79	2.59	4.23
Sr	544	602	618	496
V	29.8	26.7	19.3	21.3
Y	17.7	10.2	15.1	13.2
Zn	57.2	41.1	106.5	135.5
Zr	18.9	10.7	16.5	83.6

C.1 & 2 = Caburn Pit, Sussex; Marls 1 & 2.

Puys = between Puys and Belleville on the French coast.

Eletot = on the French coast at Eletot.

Major elements expressed in oxide weight percent, trace elements in parts per million.

N.D. = not determined.

A4.1.9 Caburn Marl.

	D.A.	C.	D.L.	P.
SiO_2	8.373	9.75	N.D.	7.524
Al_2O_3	2.392	3.068	3.032	2.263
Fe_2O_3	0.510	0.571	0.720	0.446
MnO	0.034	0.030	0.029	0.029
MgO	1.139	1.084	1.145	0.870
CaO	46.81	44.29	46.79	45.40
Na_2O	N.D.	N.D.	N.D.	N.D.
K_2O	0.200	0.321	0.364	0.248
TiO_2	0.073	0.098	0.107	0.070
P_2O_5	0.170	0.157	0.119	0.098
Ba	21.0	30.0	31.7	36.0
Cr	N.D.	N.D.	12.2	N.D.
Cu	2.0	3.0	1.7	0.3
Li	38.0	34.1	43.6	25.9
Ni	N.D.	6.5	7.8	5.9
Sc	1.09	1.67	1.42	1.10
Sr	577	522	599	604
V	12.9	20.1	19.5	13.9
Y	14.7	15.2	14.3	12.3
Zn	38.3	46.3	59.6	37.9
Zr	4.8	6.3	45.1	31.1

D.A. = Akers Steps, Dover.

C. = Caburn Pit, Sussex.

D.L. = Langdon Stairs, Dover.

P. = Between Puys and Belleville on the French coast.

Major elements expressed in oxide weight percent, trace elements in parts per million.

N.D. = not determined.

A4.1.10 Bridgewick Marls.

	B.1	B.2	D.1	D.2	P.
SiO_2	10.34	4.56	6.33	4.558	5.189
Al_2O_3	2.808	1.228	1.720	1.615	1.508
Fe_2O_3	0.735	0.298	0.389	0.404	0.335
MnO	0.027	0.027	0.033	0.030	0.026
MgO	1.157	0.667	0.975	0.879	0.845
CaO	44.06	48.59	51.07	50.63	47.84
Na_2O	N.D.	N.D.	N.D.	N.D.	N.D.
K_2O	0.150	0.125	0.191	0.219	0.166
TiO_2	0.077	0.070	0.055	0.92	0.047
P_2O_5	0.259	0.197	0.244	0.148	0.114
Ba	17.4	14.4	-17.1	18.0	15.0
Cr	2.1	1.3	N.D.	N.D.	4.9
Cu	2.4	N.D.	2.5	1.8	N.D.
Li	54.8	31.1	31.8	36.7	33.6
Ni	18.6	N.D.	5.6	10.0	12.7
Sc	1.05	0.73	0.94	0.98	0.75
Sr	433	437	494	482	510
V	12.8	9.5	10.3	11.7	8.2
Y	14.0	9.3	11.9	9.1	10.9
Zn	53.8	28.5	60.2	41.8	31.2
Zr	5.0	7.3	N.D.	2.6	3.7

B.1 & 2 = Bridgwick Pit, Sussex.

D.1 & 2 = Langdon Stairs, Dover.

P. = Between Puys and Belleville, French coast.

Major elements expressed in oxide weight percent, trace elements in parts per million.

N.D. = not determined.

A4.1.11 Lewes Marl.

	B	P	Cr
SiO_2	4.97	5.536	N.D.
Al_2O_3	1.487	1.546	2.444
Fe_2O_3	0.328	0.297	0.485
MnO	0.027	0.025	0.025
MgO	0.718	0.888	1.252
CaO	47.63	48.89	45.06
Na_2O	N.D.	N.D.	N.D.
K_2O	0.140	0.160	0.238
TiO_2	0.050	0.047	0.067
P_2O_5	0.217	0.136	0.124
Ba	12.9	11.6	15.9
Cr	N.D.	4.2	N.D.
Cu	N.D.	N.D.	0.4
Li	40.8	31.6	68.9
Ni	7.8	N.D.	8.4
Sc	0.79	0.42	0.85
Sr	476	430	413
V	10.9	8.0	7.8
Y	12.8	11.4	15.4
Zn	31.9	31.4	50.3
Zr	15.6	10.9	11.5

B = Bridgwick Pit, Sussex.

P = Puys, French coast.

Cr = Criel Plage, French coast.

Major elements expressed in oxide weight percent, trace elements in parts per million.

N.D. = not determined.

A4.1.12 White chalk samples from the French coast.

	1	2	3	4	5
SiO_2	N.D.	N.D.	N.D.	N.D.	N.D.
Al_2O_3	0.537	0.537	0.605	0.539	0.229
Fe_2O_3	0.137	0.154	0.175	0.161	0.088
MnO	0.031	0.025	0.034	0.037	0.031
MgO	0.383	0.340	0.406	0.409	0.415
CaO	54.21	53.54	49.50	54.34	55.20
Na_2O	N.D.	N.D.	N.D.	N.D.	N.D.
K_2O	0.112	0.124	0.108	0.076	N.D.
TiO_2	0.021	0.021	0.023	0.022	0.010
P_2O_5	0.059	0.071	0.080	0.133	0.067
Ba	34.7	30.2	43.8	13.0	10.5
Cr	N.D.	N.D.	N.D.	N.D.	N.D.
Cu	N.D.	N.D.	N.D.	N.D.	N.D.
Li	8.0	7.4	12.7	8.5	7.6
Ni	N.D.	N.D.	N.D.	N.D.	N.D.
Sc	N.D.	N.D.	N.D.	N.D.	N.D.
Sr	570	697	650	550	452
V	3.4	6.0	5.9	5.4.	N.D.
Y	6.0	5.6	8.9	7.7	6.8
Zn	8.6	7.9	23.8	16.2	17.6
Zr	N.D.	N.D.	6.0	N.D.	4.5

1 = 25 cm below New Pit 2.

2 = 1 m above Glynde 1[Puys].

3 = 15 cm below Caburn.

4 = 25 cm above Bridgewick.

5 = 15 cm below Lewes.

Major elements expressed in oxide weight percent, trace elements in parts per million.

N.D. = not determined.

A4.2 MARLS FROM WITHIN AND BELOW THE CHALK ROCK AND SPURIOUS CHALK ROCK.

A4.2.1 Marls collected from Burghclere.

	1	2	3	4
SiO_2	N.D.	N.D.	N.D.	N.D.
Al_2O_3	1.915	3.821	6.626	2.666
Fe_2O_3	0.539	0.821	1.217	0.628
MnO	0.037	0.030	0.023	0.035
MgO	0.490	0.725	1.477	0.613
CaO	48.35	45.30	36.44	47.94
Na_2O	N.D.	N.D.	N.D.	N.D.
K_2O	0.373	0.604	0.529	0.325
TiO_2	0.110	0.159	0.223	0.104
P_2O_5	0.210	0.162	0.130	0.115
Ba	36.7	62.3	41.0	28.8
Cr	N.D.	9.0	17.4	7.0
Cu	1.3	17.9	14.7	4.9
Li	10.3	18.0	63.7	17.4
Ni	5.5	9.2	21.2	17.8
Sc	1.97	3.24	2.57	1.45
Sr	469	444	328	441
V	16.8	24.6	35.5	20.7
Y	11.2	12.1	10.4	12.6
Zn	38.1	54.0	80.4	59.9
Zr	4.9	9.9	82.3	13.2

Major elements expressed in oxide weight percent, trace elements in parts per million.

N.D. = not determined.

A4.2.2 Marls at Beggars Knoll, Ewelme and Fognam Farm.

	B.K.1	B.K.2	E.1	E.2	F.1	F.2
SiO_2	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Al_2O_3	1.307	3.151	3.220	3.637	1.524	5.984
Fe_2O_3	0.290	0.553	0.707	0.597	0.519	0.860
MnO	0.025	0.030	0.029	0.034	0.031	0.046
MgO	0.394	0.636	0.766	1.044	0.496	1.691
CaO	50.39	45.38	42.52	42.24	49.13	37.83
Na_2O	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
K_2O	0.224	0.485	0.451	0.247	0.286	0.372
TiO_2	0.061	0.148	0.141	0.119	0.076	0.187
P_2O_5	0.108	0.197	0.143	0.135	0.106	0.277
Ba	27.9	57.3	54.2	28.4	31.5	31.1
Cr	N.D.	15.5	9.8	3.3	4.9	N.D.
Cu	N.D.	5.2	4.1	3.9	5.7	11.8
Li	5.2	13.0	14.3	23.8	5.4	23.4
Ni	4.4	7.4	N.D.	15.3	6.6	24.5
Sc	1.34	2.78	2.99	1.49	1.64	1.99
Sr	469	374	542	426	585	326
V	10.3	20.6	21.9	22.3	15.58	39.3
Y	9.7	11.5	11.5	11.9	8.6	12.7
Zn	15.7	31.6	32.7	33.0	26.7	69.8
Zr	4.3	6.0	6.5	19.7	5.5	76.8

B.K.1 & 2 = Beggars Knoll.

E.1 & 2 = Ewelme; 2 = Fognam Marl of Bromley and Gale (1982)

F.1 & 2 = Fognam Farm; 2 = Fognam Marl of Bromley and Gale (1982)

Major elements expressed in oxide weight percent, trace elements in parts per million.

N.D. = not determined.

A4.2.3 Marls collected from Kensworth.

	1	2	3	4	5
SiO_2	N.D.	N.D.	N.D.	N.D.	N.D.
Al_2O_3	3.194	1.474	2.562	4.525	2.468
Fe_2O_3	0.801	0.391	0.653	1.084	0.534
MnO	0.024	0.030	0.029	0.032	0.039
MgO	0.968	0.467	0.874	1.395	0.865
CaO	44.55	49.19	45.76	41.21	47.45
Na_2O	N.D.	N.D.	N.D.	N.D.	N.D.
K_2O	0.279	0.260	0.266	0.284	0.246
TiO_2	0.108	0.063	0.133	0.154	0.084
P_2O_5	0.110	0.137	0.122	0.221	0.154
Ba	31.1	34.9	26.4	30.0	24.9
Cr	N.D.	N.D.	N.D.	N.D.	N.D.
Cu	3.1	N.D.	3.7	4.0	5.0
Li	18.4	N.D.	6.8	37.8	7.8
Ni	7.2	3.6	1.5	11.7	7.2
Sc	1.55	1.54	1.55	1.74	1.40
Sr	526	670	505	607	577
V	16.1	11.8	18.8	20.0	19.3
Y	10.1	8.78	8.1	14.0	12.3
Zn	43.2	17.6	7.1	63.8	44.5
Zr	75.5	7.8	32.1	157.2	52.4

All samples are from below the Chalk Rock, 4 is taken from the Latimer Marl of Bromley and Gale (1982), and 5 from the Reed Marl (see log)

Major elements expressed in oxide weight percent, trace elements in parts per million.

N.D. = not determined.

A4.2.4 Marls collected from Shillingstone Hill.

	1	2	3
SiO_2	N.D.	N.D.	N.D.
Al_2O_3	1.983	3.135	2.087
Fe_2O_3	0.574	0.727	0.640
MnO	0.029	0.037	0.035
MgO	0.659	0.963	0.703
CaO	46.67	44.84	46.89
Na_2O	N.D.	N.D.	N.D.
K_2O	0.340	0.371	0.316
TiO_2	0.091	0.113	0.083
P_2O_5	0.167	0.162	0.158
Ba	37.7	32.6	32.9
Cr	N.D.	N.D.	N.D.
Cu	4.1	3.3	3.5
Li	N.D.	2.0	N.D.
Ni	5.6	9.7	7.9
Sc	1.65	1.75	1.51
Sr	507	446	507
V	16.1	28.0	22.2
Y	8.7	10.6	7.5
Zn	26.1	36.0	36.4
Zr	10.1	36.9	10.4

1. is from below the Spurious Chalk Rock, 2 & 3 are from above it (see log)

Major elements expressed in oxide weight percent, trace elements in parts per million.

N.D. = not determined.

A4.2.5 Marls collected from the Isle of Wight.

	1	2	3	4
SiO_2	N.D.	N.D.	N.D.	N.D.
Al_2O_3	5.251	4.139	3.544	1.736
Fe_2O_3	1.022	0.770	0.672	0.386
MnO	0.028	0.027	0.029	0.030
MgO	1.374	1.126	1.248	0.836
CaO	38.57	40.20	46.54	51.76
Na_2O	N.D.	N.D.	N.D.	N.D.
K_2O	0.974	0.855	0.394	0.185
TiO_2	0.232	0.169	0.114	0.059
P_2O_5	0.301	0.210	0.133	0.216
Ba	84.9	67.3	25.8	14.2
Cr	19.3	N.D.	N.D.	N.D.
Cu	13.0	6.6	1.6	0.1
Li	30.5	21.5	34.0	17.8
Ni	8.7	8.0	8.9	4.8
Sc	4.44	3.09	1.51	.91
Sr	447	435	460	437
V	33.2	29.7	27.7	12.4
Y	17.9	14.2	16.2	13.2
Zn	57.0	39.7	64.0	29.0
Zr	30.3	11.6	11.39	5.5

1 & 2 are from below the Spurious Chalk Rock, 3 & 4 are from above it and are respectively the Black Band and Grey Marl of Rowe (1908).

Major elements expressed in oxide weight percent, trace elements in parts per million.

N.D. = not determined.

A4.3 MARLS FROM THE NORTHERN PROVINCE.

A4.3.1 Grasby and Croxton Marls.

	1	2	3
SiO_2	N.D.	N.D.	N.D.
Al_2O_3	7.065	7.842	5.552
Fe_2O_3	1.701	1.671	1.269
MnO	0.029	0.025	0.025
MgO	1.726	1.722	1.321
CaO	35.83	31.52	37.96
Na_2O	N.D.	N.D.	N.D.
K_2O	0.861	1.110	1.009
TiO_2	0.568	0.369	0.142
P_2O_5	0.864	1.050	0.692
Ba	72.7	108.1	78.3
Cr	N.D.	10.4	N.D.
Cu	48.0	46.4	29.4
Li	41.4	43.5	28.1
Ni	82.0	68.3	68.2
Sc	6.09	6.81	5.01
Sr	315	340	306
V	55.8	50.0	29.3
Y	63.0	80.3	60.7
Zn	110.7	117.4	92.9
Zr	79.0	63.1	10.5

1 = Grasby Marl from Melton Ross Quarry.

2 & 3 = Croxton Marl from Melton Ross Quarry (2) and Kenwick Bar (3)

Major elements expressed in oxide weight percent, trace elements in parts per million.

N.D. = not determined.

A4.3.2 Barton Marls, Melton Ross Quarry.

	A.	B.	C.	D.
SiO_2	31.24	38.81	15.62	30.55
Al_2O_3	9.446	11.485	4.803	8.937
Fe_2O_3	1.901	3.172	0.811	1.745
MnO	0.041	0.026	0.046	0.034
MgO	2.485	2.825	1.380	2.352
CaO	31.22	23.79	45.52	29.89
Na_2O	N.D.	N.D.	N.D.	N.D.
K_2O	0.564	1.144	0.453	0.663
TiO_2	0.317	1.417	0.170	0.478
P_2O_5	0.508	0.461	0.402	0.357
Ba	47.0	81.9	38.3	44.0
Cr	11.27	N.D.	N.D.	N.D.
Cu	58.1	117.9	27.1	61.5
Li	103.8	93.7	46.0	122.6
Ni	136.8	178.4	46.5	104.3
Sc	3.89	8.20	3.21	3.68
Sr	292	245	428	308
V	31.3	118.6	21.1	46.5
Y	49.0	43.8	33.1	29.6
Zn	169.1	240.8	71.5	137.7
Zr	242.9	159.6	45.3	243.3

Major elements expressed in oxide weight percent, trace elements in parts per million.

N.D. = not determined.

A4.3.3 Barton Marls, Kenwick Bar.

	A	B	C	D
SiO_2	N.D.	N.D.	N.D.	N.D.
Al_2O_3	6.874	10.963	4.258	7.688
Fe_2O_3	1.734	3.649	0.843	1.633
MnO	0.043	0.053	0.086	0.041
MgO	2.254	2.790	1.296	2.136
CaO	35.03	22.24	42.87	32.51
Na_2O	N.D.	N.D.	N.D.	N.D.
K_2O	0.458	1.142	0.538	0.755
TiO_2	0.256	1.317	0.194	0.488
P_2O_5	0.463	0.717	0.549	0.355
Ba	37.6	91.5	43.4	40.8
Cr	N.D.	6.6	N.D.	17.5
Cu	50.6	121.7	25.5	52.6
Li	62.3	58.3	18.0	84.1
Ni	123.0	220.0	52.3	151.5
Sc	3.71	9.5	4.0	4.3
Sr	322	231	385	328
V	23.2	111.8	20.1	42.5
Y	50.8	58.9	41.4	40.4
Zn	145.0	243.5	68.4	147.0
Zr	323.1	378.8	102.5	205.3

Major elements expressed in oxide weight percent, trace elements in parts per million.

N.D. = not determined.

A4.3.4 Melton Ross and Riby Marls.

	1	2
SiO_2	42.45	45.25
Al_2O_3	12.744	12.806
Fe_2O_3	2.826	4.547
MnO	0.033	0.015
MgO	3.783	3.492
CaO	20.17	13.98
Na_2O	N.D.	N.D.
K_2O	0.445	1.246
TiO_2	0.412	1.645
P_2O_5	0.187	0.379
Ba	27.6	79.7
Cr	N.D.	N.D.
Cu	30.1	132.7
Li	238.3	167.8
Ni	81.9	182.3
Sc	4.64	8.46
Sr	243	234
V	28.2	131.8
Y	60.6	57.5
Zn	218.6	392.7
Zr	309.8	104.3

1 = Melton Ross Marl, Melton Ross Quarry.

2 = Riby Marl, Irby Dale.

Major elements expressed in oxide weight percent, trace elements in parts per million.

N.D. = not determined.

A4.3.5 Deepdale Marls.

	I.1	B.1	I.2	B.2
SiO_2	N.D.	32.16	N.D.	35.98
Al_2O_3	6.831	9.301	9.330	1.336
Fe_2O_3	1.222	1.942	2.203	2.541
MnO	0.042	0.030	0.032	0.029
MgO	2.108	2.572	2.482	2.876
CaO	36.81	29.50	26.43	22.97
Na_2O	N.D.	N.D.	N.D.	N.D.
K_2O	0.477	0.473	0.997	1.125
TiO_2	0.206	0.246	0.713	0.716
P_2O_5	0.227	0.217	0.454	0.506
Ba	37.9	30.4	90.4	78.5
Cr	10.2	N.D.	11.7	6.6
Cu	83.1	49.3	43.8	68.8
Li	117.1	169.0	125.5	140.8
Ni	35.9	57.2	82.1	90.4
Sc	3.80	3.86	5.50	6.17
Sr	443	341	320	297
V	19.9	22.2	58.8	63.4
Y	59.9	71.0	55.5	64.9
Zn	111.2	235.9	186.8	205.2
Zr	16.6	23.5	313.7	348.1

I.1 & 2 Deepdale Marls, Irby Dale.

B.1 & 2 Deepdale Marls, Burnhan Pit.

Major elements expressed in oxide weight percent, trace elements in parts per million.

N.D. = not determined.

A4.3.6 Beacon Hill, North Ormsby and Thornton Curtis Marls.

	B.H.	N.1	N.2	N.3	T.1	T.2
SiO_2	21.13	57.10	N.D.	N.D.	31.26	N.D.
Al_2O_3	6.651	14.819	14.899	16.147	9.827	10.319
Fe_2O_3	1.330.	2.691	2.972	3.091	2.360	2.231
MnO	0.024	0.010	0.009	0.009	0.034	0.038
MgO	1.739	5.465	5.792	4.692	2.295	2.895
CaO	37.85	8.49	9.83	10.05	30.22	24.98
Na_2O	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
K_2O	0.742	0.387	0.473	0.229	1.364	0.475
TiO_2	0.324	0.284	0.312	0.343	.272	0.286
P_2O_5	0.729	0.033	0.022	0.045	0.90	0.920
Ba	54.6	22.9	22.0	13.4	98.0	38.2
Cr	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Cu	53.7	17.7	29.0	20.3	67.3	62.9
Li	73.5	458.8	398.8	369.7	151.3	164.7
Ni	54.1	52.8	116.7	53.6	85.6	71.6
Sc	3.39	2.57	2.72	2.90	4.80	4.75
Sr	456	147	150	117	340	282
V	40.0	18.9	20.7	21.0	42.1	39.7
Y	51.0	51.8	53.8	62.2	51.0	52.8
Zn	126.4	199.0	286.5	227.5	164.8	192.4
Zr	147.7	257.1	1082.1	1108.5	94.2	267.6

B.H. Beacon Hill Marl, Burnham Lodge.

N.1 North Ormsby Marl, West Ravendale Pit.

N.2 North Ormsby Marl, Upper Ludborough Pit.

N.3 North Ormsby Marl, Kilnwick Percy.

T.1 Thornton Curtis Marl, Thornton Curtis.

T.2 Thornton Curtis Marl, Kilnwick Percy

Major elements expressed in oxide weight percent, trace elements in parts per million.

N.D. = not determined.

A4.3.7 Wootton Marls.

	T.C.1	N.O.1	K.P.1	T.C.2	N.O.2	K.P.2
SiO_2	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Al_2O_3	2.896	2.647	2.749	3.382	2.420	4.025
Fe_2O_3	0.771	0.884	0.825	0.812	0.930	1.161
MnO	0.064	0.065	0.065	0.050	0.060	0.069
MgO	0.861	0.855	0.901	1.051	0.914	1.211
CaO	52.61	46.78	45.62	49.05	48.00	42.36
Na_2O	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
K_2O	0.442	0.436	0.295	0.432	0.347	0.392
TiO_2	0.103	0.103	0.104	0.132	0.100	0.149
P_2O_5	0.466	0.536	0.673	0.529	0.453	0.726
Ba	39.5	33.0	28.6	38.5	27.8	32.9
Cr	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Cu	22.9	26.8	23.9	23.8	23.2	30.2
Li	25.7	9.4	1.9	43.4	14.9	23.5
Ni	36.3	56.7	37.0	30.5	41.0	49.8
Sc	2.83	2.61	2.66	3.05	2.83	3.66
Sr	506	528	490	395	440	385
V	21.6	16.8	17.8	26.2	17.9	28.4
Y	31.1	32.4	34.1	29.4	24.4	34.6
Zn	64.7	73.9	68.8	72.9	69.3	110.3
Zr	7.23	20.5	27.4	7.6	12.2	41.5

T.C.1 & 2 Wootton Marls, Thornton Curtis Pit.

N.O.1 & 2 Wootton Marls, North Ormsby Pit.

K.P.1 & 2 Wootton Marls, Kilnwick Percy Pit.

Major elements expressed in oxide weight percent, trace elements in parts per million.

N.D. = not determined.

A4.3.8 Ulceby Marl.

	U.	K.P.
SiO_2	N.D.	N.D.
Al_2O_3	5.061	7.155
Fe_2O_3	1.123	1.955
MnO	0.039	0.046
MgO	1.713	2.181
CaO	41.62	34.17
Na_2O	N.D.	N.D.
K_2O	0.466	0.433
TiO_2	0.135	0.199
P_2O_5	0.382	0.789
Ba	39.7	28.5
Cr	N.D.	N.D.
Cu	18.9	28.3
Li	75.0	101.0
Ni	25.4	44.5
Sc	3.46	4.92
Sr	399	376
V	20.8	39.3
Y	61.3	88.5
Zn	129.2	144.7
Zr	471.9	458.2

U. Ulceby Pit

K.P. Kilnwick Percy

Major elements expressed in oxide weight percent, trace elements in parts per million.

N.D. = not determined.

A4.4 GEOCHEMICAL RESULTS ACROSS NEW PIT MARL 2, BEACHY HEAD.

	N.P.1	N.P.2	N.P.3	N.P.4	N.P.5	N.P.6
SiO_2	2.66	2.89	2.83	2.16	2.29	2.09
Al_2O_3	0.537	0.550	0.501	0.378	0.387	0.354
Fe_2O_3	0.193	0.159	0.177	0.132	0.136	0.122
MnO	0.028	0.027	0.028	0.029	0.029	0.030
MgO	0.367	0.366	0.350	0.310	0.308	0.300
CaO	49.94	49.92	49.93	51.15	50.60	50.42
Na_2O	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
K_2O	0.109	0.114	0.112	0.081	0.089	0.064
TiO_2	0.040	0.037	0.030	0.021	0.019	0.019
P_2O_5	0.090	0.098	0.098	0.081	0.075	0.084
Ba	20.2	21.2	20.2	17.6	22.0	16.7
Cr	N.D.	N.D.	7.5	8.9	N.D.	N.D.
Cu	1.4	2.6	2.3	2.3	1.7	1.5
Li	5.5	6.8	7.2	4.9	N.D.	N.D.
Ni	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Sc	0.74	0.83	0.70	0.58	N.D.	N.D.
Sr	685	713	673	667	735	729
V	5.1	5.6	5.4	4.4	3.3	3.9
Y	5.5	6.2	6.2	5.2	4.9	5.4
Zn	5.1	8.2	6.5	7.3	0.9	2.5
Zr	3.4	2.8	2.7	N.D.	N.D.	N.D.

Major elements expressed in oxide weight percent, trace elements in parts per million.

N.D. = not determined.

	N.P.7	N.P.8	N.P.9	N.P.12	N.P.13	N.P.14
SiO_2	2.15	2.92	2.46	14.24	14.75	15.62
Al_2O_3	0.373	0.481	0.445	3.461	3.832	4.275
Fe_2O_3	0.125	0.221	0.150	0.697	0.979	0.933
MnO	0.029	0.029	0.037	0.032	0.033	0.028
MgO	0.315	0.328	0.351	1.076	1.089	1.181
CaO	50.29	50.17	50.67	42.48	41.85	40.87
Na_2O	N.D.	N.D.	N.D.	N.D.	N.D.	
K_2O	0.079	0.086	0.088	0.554	0.649	0.734
TiO_2	0.025	0.026	0.022	0.142	0.162	0.174
P_2O_5	0.074	0.102	0.083	0.141	0.147	0.139
Ba	15.8	19.4	15.9	51.9	62.5	72.1
Cr	N.D.	8.7	N.D.	5.2	11.6	9.0
Cu	1.4	2.5	1.2	10.8	7.2	9.5
Li	N.D.	N.D.	N.D.	21.8	22.2	26.8
Ni	N.D.	N.D.	N.D.	8.6	19.7	15.4
Sc	0.58	0.69	0.71	2.88	3.42	3.79
Sr	724	785	739	486	524	567
V	3.8	5.6	5.1	23.2	24.5	28.6
Y	5.6	7.0	7.0	12.6	13.0	12.8
Zn	2.2	8.5	7.3	133.0	37.6	52.2
Zr	N.D.	2.7	2.2	9.7	19.7	23.2

Major elements expressed in oxide weight percent, trace elements in parts per million.

N.D. = not determined.

	N.P.15	N.P.16	N.P.18	N.P.19	N.P.20	N.P.21
SiO_2	12.89	7.09	2.19	2.32	2.87	2.60
Al_2O_3	3.123	1.642	0.389	0.426	0.474	0.424
Fe_2O_3	0.698	0.403	0.127	0.211	0.151	0.157
MnO	0.027	0.030	0.030	0.029	0.028	0.027
MgO	0.943	0.671	0.368	0.361	0.341	0.341
CaO	42.77	47.77	52.17	51.28	50.74	51.89
Na_2O	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
K_2O	0.573	0.285	0.070	0.075	0.095	0.086
TiO_2	0.138	0.075	0.017	0.018	0.020	0.020
P_2O_5	0.169	0.122	0.045	0.049	0.091	0.076
Ba	61.2	38.0	14.9	16.8	19.5	16.39
Cr	7.6	4.0	N.D.	N.D.	N.D.	N.D.
Cu	18.8	5.7	1.3	1.3	1.3	1.2
Li	19.5	8.8	N.D.	N.D.	N.D.	N.D.
Ni	8.5	4.2	N.D.	N.D.	N.D.	N.D.
Sc	2.8	1.7	N.D.	N.D.	0.57	N.D.
Sr	552	521	572	547	710	645
V	23.2	12.7	N.D.	3.9	4.6	4.4
Y	13.1	10.2	5.5	5.6	6.3	5.8
Zn	49.5	26.2	944.9	2.9	28.5	6.8
Zr	17.4	5.8	N.D.	N.D.	1.8	2.8

Major elements expressed in oxide weight percent, trace elements in parts per million.

N.D. = not determined.

4.5 CARBONATE ASSOCIATED ELEMENTS; NEW PIT MARL 2, BEACHY HEAD.

	N.P.1	N.P.2	N.P.3	N.P.4	N.P.5	N.P.6
Al	5.3	8.6	7.6	2.5	8.2	4.3
Fe	164.3	156.5	156.4	170.2	185.8	191.9
Mn	175.4	167.5	179.7	189.2	188.1	207.2
Mg	974.0	958.3	991.8	922.2	942.3	948.5
Ca	27.01	26.38	26.27	25.85	26.72	27.30
Sr	602.5	619.3	591.6	590.9	642.7	676.8
Ba	1.61	2.12	1.59	1.75	5.05	1.88
Zn	8.0	6.7	10.3	10.8	7.0	13.0

All results in parts per million (Ca x10^4)

N.D. = not determined.

	N.P.7	N.P.8	N.P.9	N.P.12	N.P.13	N.P.14
Al	6.8	4.3	15.5	60.8	63.3	85.4
Fe	166.0	145.9	163.2	120.9	109.0	80.4
Mn	188.7	187.0	251.7	201.2	204.9	171.3
Mg	911.0	857.6	1045.6	1369.2	1243.9	1196.9
Ca	26.38	26.01	27.28	22.08	21.89	21.40
Sr	644.4	703.3	716.0	431.0	457.1	495.3
Ba	0.79	1.79	2.54	8.48	2.27	4.41
Zn	9.7	8.2	16.0	22.5	15.1	17.0

All results in parts per million (Ca x10⁴)

N.D. = not determined.

	N.P.15	N.P.16	N.P.18	N.P.19	N.P.21
Al	72.1	25.5	4.6	5.5	9.4
Fe	103.4	173.7	175.0	181.7	159.4
Mn	173.7	191.0	199.3	191.0	180.0
Mg	1244.1	1296.0	1124.3	1060.9	994.9
Ca	22.86	24.84	27.57	27.39	27.03
Sr	488.2	455.6	511.1	532.0	617.6
Ba	4.84	3.94	0.89	1.42	1.08
Zn	18.8	12.6	12.4	11.4	1.08

All results in parts per million (Ca x10^4)

N.D. = not determined.

A4.6 STABLE ISOTOPE AND TOTAL ORGANIC CARBON RESULTS.

A4.6.1 Isotope and TOC results across New Pit Marl 2, Beachy Head.

	$\delta^{13}C$ (PDB)	$\delta^{18}O$ (PDB)	T.O.C.
NP 1	2.253	-2.863	(wt.%)
NP 2	2.289	-2.784	
NP 3	2.241	-2.964	
NP 4	2.193	-3.243	0.273
NP 5	2.198	-3.111	0.154
NP 6	2.127	-3.200	0.212
NP 7	2.196	-3.195	0.139
NP 8	2.138	-3.339	0.160
NP 9	2.113	-3.365	0.760
NP 12	2.132	-2.195	0.168
NP 13	2.072	-2.144	0.144
NP 14	2.117	-2.126	0.164
NP 15	2.143	-2.167	0.208
NP 16	2.131	-2.646	0.185
NP 18	2.044	-3.549	0.306
NP 19	2.050	-3.453	0.360
NP 20	2.099	-3.200	0.165
NP 21	2.099	-3.030	0.154

A4.6.2 Isotope results of selected marls and white chalks.

	$\delta^{13}C$ (PDB)	$\delta^{18}O$ (PDB)
New Pit 1, Beachy Head	2.324	-2.340
New Pit 2, Beachy Head	2.072	-2.144
White chalk, Beachy Head	2.099	-3.200
New Pit 1, Dover	2.282	-2.492
New Pit 2, Dover	2.159	-2.558
White chalk, Dover	2.151	-2.676
Glynde 2 [Dover]	1.604	-2.648
White chalk, Dover	1.840	-3.305
Glynde 1 [Puys]	1.538	-1.938
White chalk, Puys	1.611	-3.136
Southerham 1, Eletot	1.445	-1.868
White chalk, Eletot	1.480	-3.130
Caburn, Eletot	1.369	-2.174
White chalk, Eletot	1.118	-2.761

N.B. white chalk samples were collected adjacent to the marls which are above them in the table.

A4.7 RARE-EARTH ELEMENT RESULTS FROM SELECTED TURONIAN MARLS.

	La	Ce	Pr	Nd	Sm
NP 21	5.4	3.9	0.72	3.0	0.79
NP 18	4.7	4.1	0.58	2.7	0.57
NP 14	13.3	17.6	2.82	11.7	2.54
NP 8	6.5	5.8	0.69	4.3	0.54
NP 4	5.2	3.9	0.61	2.6	0.43
Lewes	12.6	19.4	3.07	13.6	3.02
Bridgewick 2	8.0	11.3	1.86	7.6	1.41
Bridgewick 1	10.7	19.2	3.20	13.0	2.93
Caburn	14.5	25.9	4.39	15.9	3.63
Southerham 2	9.9	12.5	1.97	8.4	1.68
Southerham 1	14.4	26.1	4.39	16.1	3.65
Glynde 1	12.5	23.3	3.71	15.1	3.38
New Pit 2	13.1	15.8	2.54	11.8	2.70
New Pit 1	12.1	13.6	2.33	10.5	2.35
G.C. Above	57.3	84.0	14.46	66.7	15.22
G.C. Marl	30.8	66.5	11.61	44.1	10.03
G.C. Below	81.8	141.8	24.61	109.7	25.86
Chondrite	0.24	0.64	0.096	0.44	0.15
Shale	41	83	10.1	38	7.5

NP 18 & 21 = above New Pit 2, Beachy Head.

NP 14 = New Pit 2, Beachy Head.

NP 4 & 8 = below New Pit 2, Beachy Head.

Turonian marls all collected in Sussex

G.C. = insoluble residues from below, within and above Southerham Marl 1, Great Chesterford.

Chondrite = chondrite from Evensen *et al.* (1978)

Shale = average shale from Piper (1974)

	Eu	Gd	Dy	Ho	Er
NP 21	0.24	0.76	0.65	0.24	0.37
NP 18	0.12	0.46	0.62	0.15	0.34
NP 14	0.47	2.20	1.75	0.42	0.85
NP 8	0.22	0.91	0.86	0.37	0.55
NP 4	0.12	0.55	0.58	0.27	0.34
Lewes	0.39	2.42	2.13	0.45	1.11
Bridgewick 2	0.29	1.35	1.12	0.23	0.54
Bridgewick 1	0.41	2.51	2.10	0.44	1.12
Caburn	0.45	2.78	2.45	0.48	1.23
Southerham 2	0.35	1.48	1.32	0.38	0.58
Southerham 1	0.48	2.80	2.84	0.62	1.61
Glynde 1	0.48	2.52	2.03	0.39	0.85
New Pit 2	1.10	2.15	1.77	0.39	0.87
New Pit 1	0.41	1.85	1.63	0.29	0.84
G.C. Above	2.53	15.93	10.64	2.19	5.50
G.C. Marl	1.42	7.71	5.73	1.16	2.82
G.C. Below	4.22	22.08	15.92	3.20	7.73
Chondrite	0.06	0.20	0.25	0.06	0.17
Shale	1.61	6.35	5.50	1.34	3.75

NP 18 & 21 = above New Pit 2, Beachy Head.

NP 14 = New Pit 2, Beachy Head.

NP 4 & 8 = below New Pit 2, Beachy Head.

Turonian marls all collected in Sussex

G.C. = insoluble residues from below, within and above Southerham Marl 1, Great Chesterford.

Chondrite = chondrite from Evensen *et al.* (1978)

Shale = average shale from Piper (1974)

	Yb	Lu
NP 21	0.30	0.07
NP 18	0.33	0.02
NP 14	0.80	0.09
NP 8	0.47	0.10
NP 4	0.27	0.02
Lewes	0.85	0.10
Bridgewick 2	0.54	0.06
Bridgewick 1	0.92	0.10
Caburn	1.55	0.12
Southerham 2	0.61	0.07
Southerham 1	1.51	0.18
Glynde 1	0.78	0.11
New Pit 2	0.82	0.14
New Pit 1	0.71	0.09
G.C. Above	3.20	0.38
G.C. Marl	2.00	0.23
G.C. Below	5.08	0.60
Chondrite	0.17	0.03
Shale	3.53	0.61

NP 18 & 21 = above New Pit 2, Beachy Head.

NP 14 = New Pit 2, Beachy Head.

NP 4 & 8 = below New Pit 2, Beachy Head.

Turonian marls all collected in Sussex

G.C. = insoluble residues from below, within and above Southerham Marl 1, Great Chesterford.

Chondrite = chondrite from Evensen *et al.* (1978)

Shale = average shale from Piper (1974)

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October 1990

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